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# DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

## CORROSION AND BIOFOULING ON THE NON-HEAT-EXCHANGER SURFACES OF AN OCEAN THERMAL ENERGY CONVERSION POWER PLANT A SURVEY

Edited by

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Prepared for Pacific Northwest Laboratory
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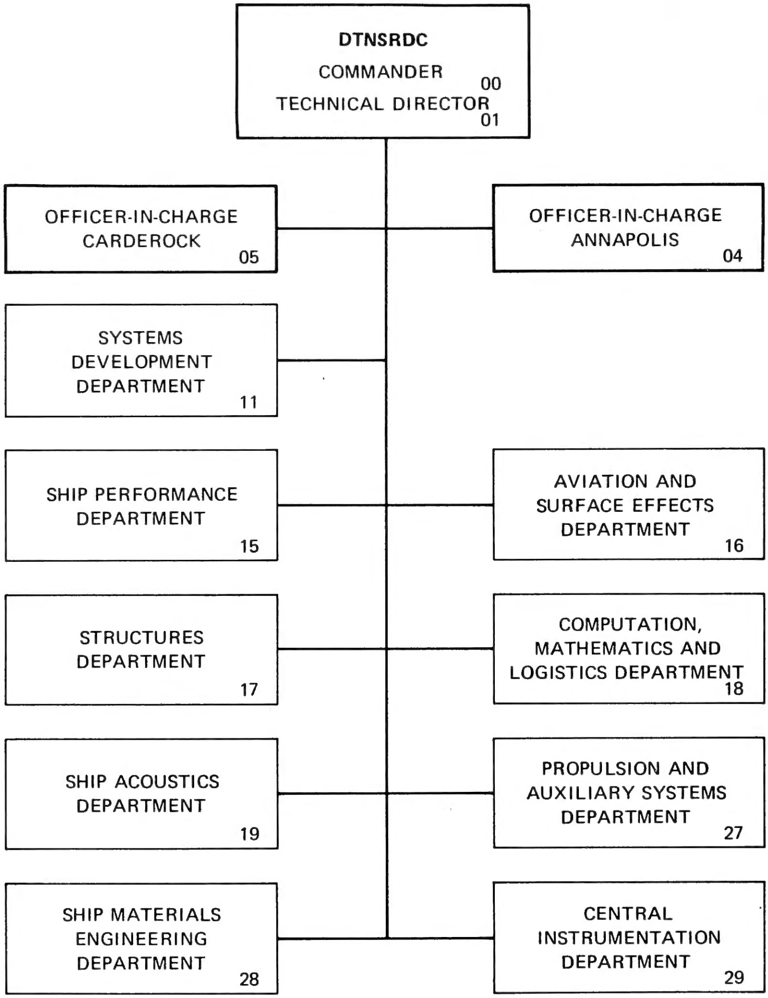

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Of the many foreseeable problems confronting economical ocean thermal energy conversion operation, two major items are the deterioration of the structural and functional components, which prevents efficient operation, and the biofouling of the surfaces, which adds excess weight to the floating ocean platform. The techniques required for effective long-term control of deterioration and corrosion have been investigated actively for many years,
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and successful solutions for most situations have been developed. For the most part, these solutions can be directly transferred to the ocean thermal energy conversion plant. The majority of problems in these areas are expected to be associated with scale-up and will require some advanced development due to the immensity of the ocean thermal energy conversion platform.

Current antifouling control systems are not effective for long-term fouling prevention. Commercially available antifouling coatings are limited to a 3-year service life in temperate waters, and even shorter in tropical waters. However, underwater cleaning techniques and some fouling-control systems presently being used by conventional power plants may find utility on an ocean thermal energy conversion plant. In addition, some recent major advances in long-term antifouling coatings sponsored by the Navy may be applicable to ocean thermal energy conversion.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| AF | Antifouling |
| AISI | American Iron and Steel Institute |
| ASTM | American Society for Testing and Materials |
| cm | Centimeters |
| DOE | Department of Energy |
| FRP | Fiber-reinforced plastic |
| ft/s | Feet per second |
| $g/m^2$ | Grams per square meter |
| GRP | Glass-reinforced plastic |
| l/min | Liters per minute |
| LMSC | Lockheed Missiles and Space Company, Inc. |
| m | Meters |
| $mA/ft^2$ | Milliamperes per square foot |
| ml/l | Milliliters per liter |
| MPa | Megapascals |
| mpy | Mils per year |
| m/s | Meters per second |
| mV | Millivolts |
| MW | Megawatts |
| NCEL | Naval Civil Engineering Laboratory |
| NRL | Naval Research Laboratory |
| OMP | Organometallic polymer |
| OTEC | Ocean thermal energy conversion |
| PC | Polymer concrete |
| PIC | Polymer-impregnated concrete |

| | |
|---|---|
| ppm | Parts per million |
| prepreg | Preimpregnated |
| psi | Pounds per square inch |
| ROSCM | Research Organization of Ship's Compositions Manufacturers Ltd. |
| SCAMP | Submerged cleaning and maintenance platform |
| SPC | Self-polishing copolymer |
| TBTF | Tributyltin fluoride |
| TBTO | Tributyltin oxide |
| TOTO | Tongue of the Ocean |
| TPhTF | Triphenyltin fluoride |
| V | Volts |
| W/C | Water/cement ratio |

ABSTRACT

Of the many foreseeable problems confronting economical ocean thermal energy conversion operation, two major items are the deterioration of the structural and functional components, which prevents efficient operation, and the biofouling of the surfaces, which adds excess weight to the floating ocean platform. The techniques required for effective long-term control of deterioration and corrosion have been investigated actively for many years, and successful solutions for most situations have been developed. For the most part, these solutions can be directly transferred to the ocean thermal energy conversion plant. The majority of problems in these areas are expected to be associated with scale-up and will require some advanced development due to the immensity of the ocean thermal energy conversion platform.

Current antifouling control systems are not effective for long-term fouling prevention. Commercially available antifouling coatings are limited to a 3-year service life in temperate waters, and even shorter in tropical waters. However, underwater cleaning techniques and some fouling-control systems presently being used by conventional power plants may find utility on an ocean thermal energy conversion plant. In addition, some recent major advances in long-term antifouling coatings sponsored by the Navy may be applicable to ocean thermal energy conversion.



ADMINISTRATIVE INFORMATION

This work was accomplished under Work Unit 2853-501 and was sponsored by the Department of Energy. It was initiated as part of the Biofouling and Corrosion Project administered under Agreement RL-76-9599 by Drs. Lyle D. Perrigo and George A. Jensen of the Pacific Northwest Laboratory, Richland, Washington 99352. This Laboratory is operated for the U.S. Department of Energy by Batelle Memorial Institute.


## INTRODUCTION

### BACKGROUND

The Department of Energy (DOE) currently is investigating several power-generating techniques as alternatives to conventional fossil-fueled and nuclear power plants. One of the several proposed techniques would

extract energy by using the thermal differential between warm ocean surface waters and cooler deep ocean waters (Ocean Thermal Energy Conversion (OTEC)). Preliminary conceptualizations were presented in significant detail by groups at both Carnegie-Mellon University[1-4*] and the University of Massachusetts.[5,6] The studies demonstrated that the technical framework for such an undertaking was clearly available. These data were drawn upon heavily by both the Lockheed Missiles and Space Company, Inc.[7] (LMSC) and by TRW, Inc.,[8] to provide balanced technical and economic feasibility studies, and design conceptualizations based on capabilities available in industry today.

The design concepts published by both LMSC** and TRW placed heavy emphasis on the use of construction materials which have been proven reliable after extensive application in the marine environment, and only suggested developmental materials where they were believed to be essential, for either structural or economic reasons. It is not surprising that both technical groups relied heavily upon steel-reinforced concrete, various steels, and fiber-reinforced composites for the basic structure (exclusive of the heat exchangers and associated power-generating equipment). These materials must be considered critically before firm commitments to their use are considered. The two areas of concern relate to: (1) resistance to deterioration in response to prolonged immersion in seawater, and (2) possible methods for mitigating what is expected to be a high rate of fouling.

## OBJECTIVE

The objective of this report is to provide a summary evaluation of the research and development directed toward the prevention of deterioration and biofouling that would be of interest to an OTEC designer. A significant effort previously has been expended to obtain these data, especially the evaluations of alloys, composites, organic materials, and concretes for their ability to resist deterioration and corrosion in the marine environment, and additionally, techniques to prevent, control, and remove fouling

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*A complete listing of references is given on page 69.

**Definitions of abbreviations used are given on page vii.

from submerged surfaces. These data have been the stock in trade of the various groups that design and construct marine equipments and structures. For effective utilization in the design of an OTEC plant, there exists a requirement for a single comprehensive survey of all this information. The information in many cases is well documented; its incorporation during design phases should be straightforward. However, several significant gaps exist in our present knowledge. Some deficiencies have to do with scale-up of presently used techniques. These areas will be identified, and it is suggested that the information provided be used only as a guide until hard experimental data are available.

## SCOPE

This survey covers two basic areas: the deterioration of materials and the control of biofouling. The primary interest in the former is the performance of concrete, low-alloy steels, and fiber-reinforced plastics, and the use of anticorrosion coatings to protect steel and special alloys. Emphasis in the latter area is on the nature of fouling, suggested anti-fouling coatings for all types of surfaces, inherently antifouling materials of construction, and fouling removal techniques.

# MATERIALS OF CONSTRUCTION

## CONCRETE

Concrete has been proposed for construction of the OTEC power plant platform.[7] The platform could be deployed on the surface of the ocean[8] or submerged several hundred feet with an access tower penetrating the surface of the ocean.[7] The platform provides a structure on which to secure the power modules and the cold seawater pipe, to provide storage facilities, and to house operating personnel and auxiliary equipment in a dry 1-atmosphere environment. The cold seawater pipe, as large as 130 ft in diameter, transports large volumes of cold seawater drawn from as mush as 4000 ft deep. The warm seawater ducting is an integral part of the upper portion of the platform.[7]

Nature of Concrete

Concrete is a complex composite consisting of Portland cement, aggregate of varying sizes and types, and sufficient water to permit a series of chemical reactions to occur. Concrete structures are usually strengthened by embedding reinforcement in the composite. Reinforcements such as steel rod (rebar), wire and wire mesh, and various fiber materials increase its tensile strength. Concrete, as it is usually made, is more or less porous and permeable to moisture. Its resistance to penetration by moisture can be much increased by choosing appropriate types of cement and aggregate for its preparation and by the method of emplacement. Relatively short-term protection against moisture and water absorption can be provided by coatings applied to the outer surface of the concrete.

The durability of concrete is defined as its long-term resistance to deterioration and to corrosion of embedded steel reinforcement. Factors affecting concrete durability have been identified by Browne,[9] Haynes and Rail,[10] and Lorman.[11] Sulfate ions in seawater react with certain cements to form calcium sulfo-aluminate with resultant crystal growth and concrete[9] disruption. Cements containing more than 8-percent tricalcium aluminate (C3A) have poor resistance to sulfates in seawater.[11] ASTM Type V Portland cement contains an allowable maximum of 8 percent by weight of C3A. Although ASTM Type II Portland cement performs satisfactorily in seawater, either ASTM Type V or a Pozzolanic cement is preferable for marine installations in tropical or semitropical regions.[11]

Another aspect, the water-cement ratio (W/C) is an important factor in the durability of concrete. To ensure a low permeability the W/C should not exceed 0.5 by weight.[9] For example, with concretes having a W/C of 0.4 by weight and subject to a hydrostatic head of 1 ft, saturation to a depth of 2 in. occurs in about 5 yr.

Closely related to W/C is the cement content or weight of cement per cubic yard of concrete. Concrete structures exposed to seawater should be dense, impervious, relatively nonabsorbent, and have a minimum cement content of 6 1/2 and a maximum of 7 1/2 bags per cubic yard[12] (one bag contains 94 lb of cement). Another important factor affecting the durability of concrete is corrosion of embedded steel (rebar) reinforcement. An excellent discussion on the corrosion of reinforcing bars in concrete

has been presented by Mozer, et al.[13] Steel cast in concrete quickly develops a passivating iron oxide film that prevents further corrosion. Passivation of the steel is provided by the high alkalinity (pH 12.8) of lime produced by the hydration of cement.[9] Corrosion of rebar occurs if failure (cracking) or porosity of the concrete allows chloride ions (electrolyte) to penetrate ot the surface of the rebar, and depends also on other factors such as the availability and concentration of oxygen, and number and size of voids adjacent to the rebar.[12] Figure 1 is a schematic representation of the conditions at the rebar surface when an electrolyte penetrates and forms an electrolytic macrocell in the concrete.[11]

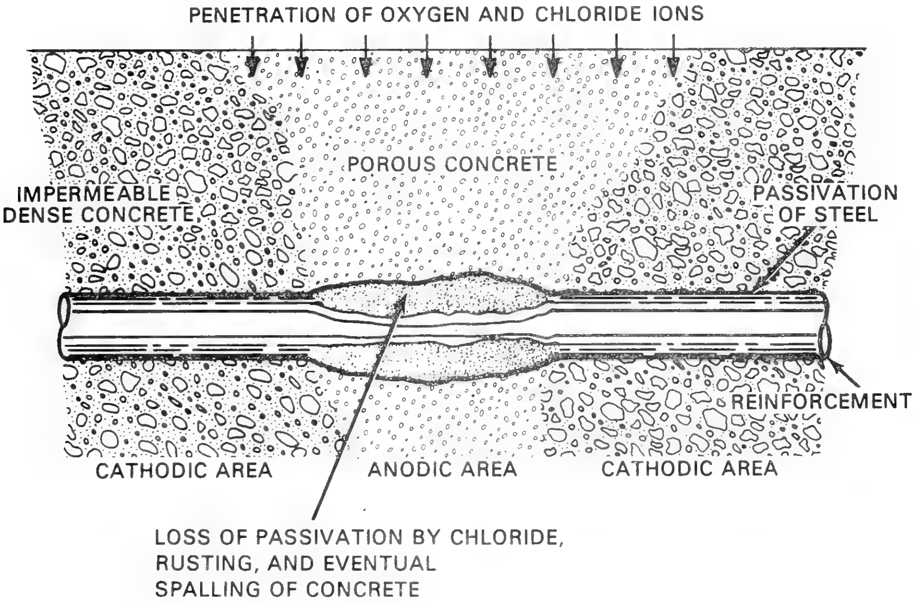


Figure 1 - Electrolyte Macrocell in Reinforced Concrete Causing Spalling

Corrosion resistance may be enhanced by metallic (i.e., zinc or nickel) coatings on rebar embedded in concrete submerged in seawater. In reviewing the technology, Lorman[11] noted that long-term tests have revealed

that the initial attack on zinc by the alkalies released during hydration of the cement is not progressive and that the coating can be expected to have good durability. Concrete alkalinity is initially corrosive to the zinc coating, forming a layer of zinc hydroxide, and subsequently a complex calcium zincate which is insoluble in the highly alkaline pore liquid in the concrete. The chemical reaction produces a tight bond between the concrete and the zinc-coated steel and provides a barrier against further alkali attack on the underlying zinc. However, the reaction between zinc and the alkaline pore liquid of freshly placed concrete can form bubbles of hydrogen gas which would have an adverse effect on the bond strength in normal reinforced concrete. It has been observed that a small amount of chromate in the cement, or dipping the galvanized steel in a chromate bath, suppresses the evolution of hydrogen. The concentration of chromates in the pore liquid that is necessary to inhibit the formation of hydrogen is very low, on the order of 70 ppm in the cement paste, corresponding to a soluble chromate content of 0.014 percent (by weight) in the dry cement, assuming a W/C of 0.5. Since some Portland cements are low in chromate, chromate-coated galvanized steel should be used with all cements.

Baker, et al,[14] reported results of an 11-yr study of bare steel and nickel- and zinc-coated steel rebars embedded in concrete castings exposed in the seawater tidal zone. Steel rebar materials were ASTM A-615 steel, a high-strength, low-alloy Ni-Cu-Cr steel, and AISI 4340 steel. The concrete castings were formulated with ASTM Types I and II Portland cement. The specimens were exposed in the seawater tidal zone, which allowed them to be alternately wet and dry twice each day, and simulated the exposure of reinforced pilings or structures in seawater. The results show that metallic coatings on rebar are definitely beneficial compared to bare carbon or bare low-alloy steels. They also show that a 1-mil nickel coating is sufficient to achieve improved reinforced concrete performance. That study did not reveal any particular advantage in the use of a low-alloy steel over carbon-steel-reinforcing bars.

Rebar corrosion can also be prevented by providing an adequate concrete cover. A minimum 3-in.-thick cover for plane and curved surfaces and a 4-in.-thick cover at corners has been recommended.[13] Browne[9] concluded that, for a very wide range of marine applications, reinforced concrete

made with the right materials and mix proportions, and placed correctly with adequate and well compacted cover, was a durable, long-lasting material requiring little maintenance.

## Recent Developments in Concrete Technology

Polymer concrete and polymer-impregnated concrete are recent developments in concrete technology that may have application to OTEC power plant structures and components. Polymer concrete (PC) consists of cement and an aggregate mixed with a monomer resin which is subsequently polymerized in place.[15] Manson[16] defines polymer concrete as a composite in which a thermoplastic or cross-linked polymer is used to replace all or part of the Portland cement as the binder in a concrete mix. Techniques for mixing and placement are similar to those used for Portland cement. After curing, a high-strength, durable material results. Kukacka and Steinberg[17] reported several important properties of PC measured on specimens containing oven-dried aggregate and containing 7- to 8-percent monomer by total weight of wet mix. The enhanced durability properties are significant; for example, water absorptions of 1 percent are normally obtained.

Keeton and Alumbaugh[15] investigated the strength and strength-ratio properties of polymer-cement mortar and polymer-cement-concrete composites formulated with (1) epoxy, polyester, and epoxy-acrylate resins; (2) acrylic, vinyl acetate, styrene-butadiene, and polyvinylidene chloride latices in varying proportions in relation to the weight of the cement. ASTM Type III Portland cement and regulated set cements were used. Compressive strength values are summarized in Table 1.

Polymer-impregnated-concrete (PIC)[15] is the most highly developed of the concrete-polymer composites and provides the greatest improvements in structural and durability properties. For a straight concrete mix which produces specimens with compressive strengths of 35 MPa (5000 psi), compressive strengths of 140 MPa (20,000 psi) are generally obtained after impregnation with monomer and subsequent curing. Design values for PIC that cover the range of monomer systems used and other types of concrete have been published.[15] These values are summarized in Table 1.

TABLE 1 - SELECTED PROPERTIES OF CONCRETE,[14] POLYMER CONCRETE,[15] AND POLYMER-IMPREGNATED CONCRETE[15]

| | Concrete | | PC | | PIC | |
|---|---|---|---|---|---|---|
| | MPa | psi | MPa | psi | MPa | psi |
| Compressive Strength | 33.3 | 5,000 | 24-138 | 3,500-20,000 | 100 | 15,000 |
| Tensile (splitting) Strength | - | - | 9.6 | 1,400 | - | - |
| Tensile (direct) Strength | 2.8 | 400 | - | - | 7 | 1,000 |
| Modulus of Elasticity | 23,600 | $3.5 \times 10^6$ | 36,000 | $5.3 \times 10^6$ | 41,000 | $6.0 \times 10^6$ |
| Shear Strength | - | - | - | - | 5 | 750 |
| Modulus of Rupture | - | - | - | - | 9 | 1,300 |
| Poisson's Ratio | - | - | 0.23 | 0.23 | 0.20 | 0.20 |

Additional research and development are needed to determine the following properties of PIC and to prove its practicability: (1) splitting tensile strength, (2) flexural strength, (3) Young's modulus, (4) water tightness, and (5) sulfate resistance.

Technology Deficient Areas

Haynes and Rail,[10] in their study of concrete for OTEC structures, summarized the capacities and limitations of available concrete technology and construction practices and identified deficiency areas. Areas that have been identified as requiring further research and development to provide improvements in concrete technology, greater assurances for long-term safe and reliable operation of OTEC systems, and lower cost structures are listed:

1. Penetration of concrete by seawater
2. Lightweight concrete
3. Rapid analysis of fresh concrete
4. Encironmental load criteria
5. Hydrostatic loadings
6. Design for shear, fatigue, and impact
7. Prestressing systems
8. Construction methods and inspection procedures.

## STEELS

Alloy steels are candidate construction materials for the OTEC cold and warm seawater piping and the power module housing. The marine environment considered for their deployment is the splash and spray zone, surface and near-surface seawater, and depths to 4000 ft.

A wide range of such steels is available from which designers can select to meet the mechanical and other requirements of a specific installation. An important factor affecting the choice of materials for use in the marine environment is its corrosion characteristics. Corrosion characteristics of various steels have been studied for many years, and results have been published in numerous texts and technical journals.

### Corrosion in the Marine Environment

Boyd and Fink[18] summarized the corrosion characteristics of a variety of carbon and low-alloy steels in the splash and spray zone, surface seawater, and in the deep ocean. Factors affecting corrosion in seawater are summarized in Table 2.[19] When metal structures are exposed to ocean environments, certain types of corrosive attack are common. The most common forms of corrosion of low-alloy steels are: (1) uniform (general), (2) pitting, and (3) galvanic corrosion. Galvanic corrosion and its control are discussed separately in a later section.

TABLE 2 - MAJOR FACTORS AFFECTING CORROSION IN SEAWATER ENVIRONMENT*

| Chemical | Physical | Biological |
| --- | --- | --- |
| Dissolved Gases(1) | Velocity(3) | Biofouling(5) |
| Oxygen | Air Bubbles | Hard Shell Types |
| Carbon Dioxide | Suspended Silt | Types without Hard Shells |
| | | Mobile and Semimobile Types |
| Chemical Equilibrium(2) | Temperature(4) | Plant Life |
| Salinity | | Oxygen Generation |
| pH | | Carbon Dioxide Consumption |
| Carbonate Solubility | | |
| | | Animal Life |
| | | Oxygen Consumption |
| | | Carbon Dioxide Generation |

*Using iron as reference, the following trends are typical:

(1) Oxygen is a major factor in promoting corrosion.
(2) The tendency to form protective scale (carbonate-type) increases with higher pH.
(3) Increasing velocity tends to promote corrosion, especially if entrained matter is also present.
(4) Temperature increase tends to accelerate attack.
(5) Biofouling can reduce attack or promote local corrosion cells.

Uniform corrosion is the wasting or thinning of a metal surface exposed to a corrodant. Attach occurs evenly over the exposed surfaces. The rate of uniform attach (a measure of metal loss or penetration) is usually reported as mils (0.001 in.) per year (mpy) and is represented by time-averaged values. Because the initial rate of attack is often greater than the final rate, exposure time has to be considered in evaluating data. Pitting is localized attack where the corrosion is greater in some areas than in others. During immersion, factors leading to pitting are: (1) relatively stagnant environment, (2) higher dissolved oxygen content, and (3) local deposits of foreign matter. Galvanic corrosion results from the electrical interconnection of metals with differing potentials, with subsequent dissolution of the least noble metal.

## Corrosion Characteristics

Corrosion of steel as a function of marine environmental conditions is illustrated in Figure 2.[19]

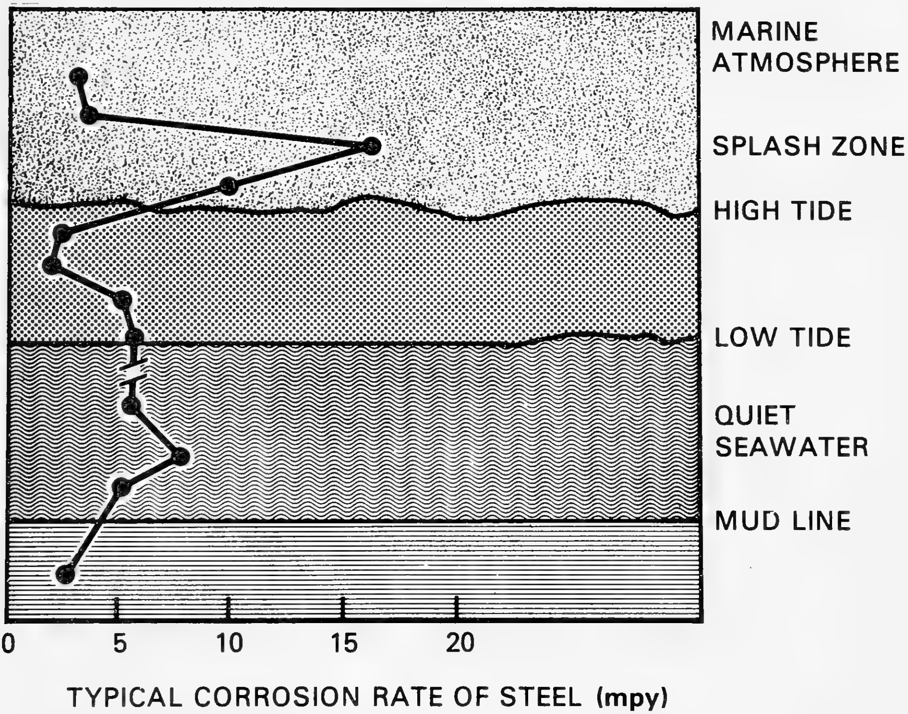


Figure 2 - Corrosion of Steel in the Marine Environment

The splash zone is most aggressive since materials are generally in contact with aerated seawater resulting from wave action. Air bubbles tend to make the environment more aggressive by removing protective films or dislodging coatings.[18]

Steels continuously immersed in seawater corrode at a uniform rate, averaging 5 mpy.[20] Long-term data show that the corrosion rate actually decreases to values below 5 mpy.[18]

The most important factor influencing the corrosion of steels in seawater is the dissolved oxygen content. The change in concentration of oxygen in seawater with depth is shown in Figure 3[21] for two specific locations in the Atlantic and Pacific Oceans. It illustrates the requirement for data on the actual oxygen concentration at the desired depth for a specific location of interest. Reinhart[22,23] and Wheatfall[24] showed that, at depths where dissolved oxygen concentrations varied, the rate of corrosion of steels was closely related to the concentration of dissolved oxygen. This is illustrated in Figure 4[21] for carbon and low-alloy steels exposed for 1 yr in the Pacific Ocean. Also in deep waters with lower oxygen content, the morphology of attack on steel is more uniform and less rough than at the surface.[24]

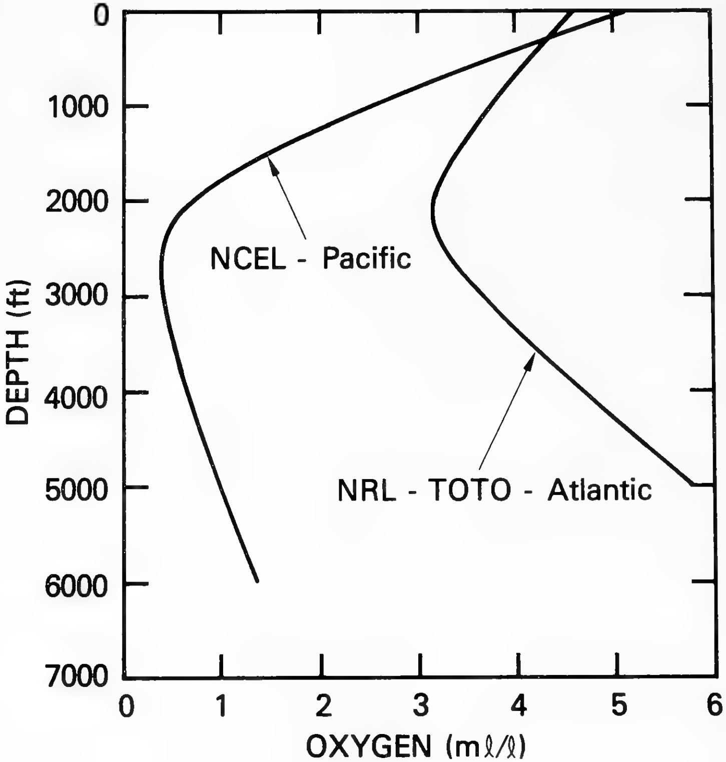


Figure 3 - Change in Concentration of Oxygen in Seawater with Depth

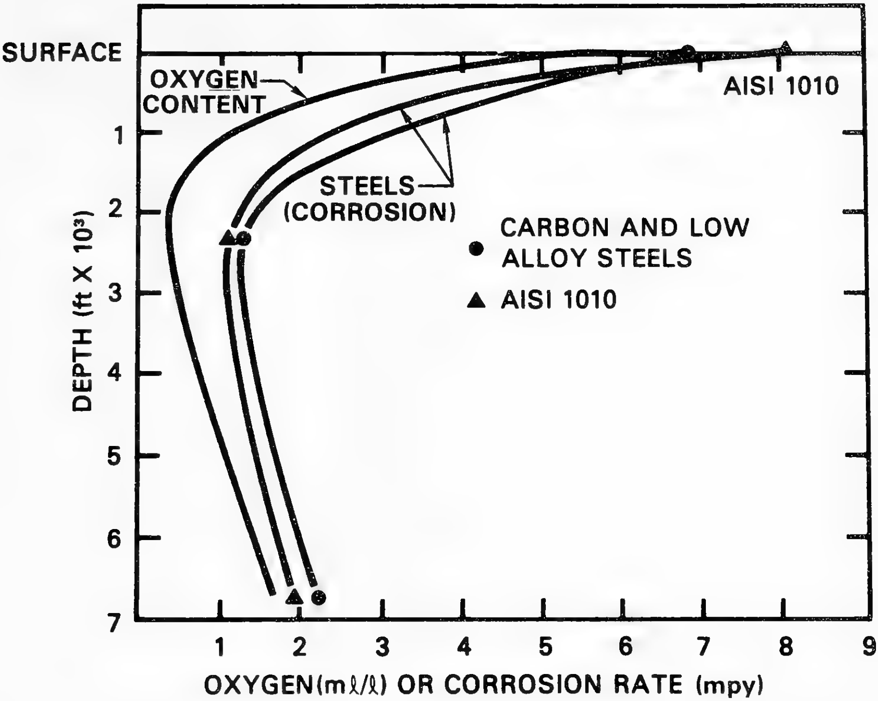


Figure 4 - Corrosion of Steels Versus Depth
After 1 Year of Exposure

Fouling and Its Effect on Corrosion

Steel structures foul in seawater. The rate of fouling is a function of depth; less fouling occurs in deep waters. Attachment and growth of marine organisms influence the rate of steel corrosion in seawater,[25] as indicated by the results obtained in a 16-yr investigation in Panama.[26] The long-term data reveal the protective effect of microfouling against normal corrosion and the development of constant-rate bacterial corrosion. The study suggests that selective control of marine bacteria could be a key factor in achieving very low corrosion rates of structural steel in seawater.[25]

Galvanic Interactions and Cathodic Protection

The possibility of galvanic corrosion of the more anodic components must be considered wherever dissimilar metals are used in marine construction. If structural requirements preclude use of galvanically compatible materials, electrical isolation of the members or cathodic protection must be used to counteract these galvanic effects. Figure 5 ranks the corrosion potentials of some commonly used alloys. These alloys listed higher up (more negative) will corrode sacrificially when electrically connected to an alloy lower down (more positive) in this table.

The relationship and countermeasures are illustrated by the use of bronze propellers on steel ships. The steel hull (anode) is painted for protection, and sacrificial or impressed current anodes are used to supply current to the steel and the propeller (cathode). In this situation, cathodic protection reduces corrosion of both the steel and bronze. If the galvanic effect of the propeller were not counteracted cathodically, accelerated corrosion in the form of pitting would occur at paint holidays on the steel.

Cathodic Protection of Steels

It will be necessary to cover steel members with protective coatings and provide cathodic protection to prevent localized pitting and decrease the rate of general corrosion. The required current capacity for cathodic protection depends on the severity of environment, and the requirement increases significantly with water resistivity, flow, and turbulence. Table 3 illustrates the range in these parameters which can be encountered.

Techniques for an OTEC Plant

If replaceable steel modules are used, cathodic protection can be maintained with sacrificial anodes of zinc or aluminum. It is now practical to design for lifetimes of 10 to 20 years with current technology. Aluminum anodes are the most effective as the amount of time-weighted protective current available per unit weight (ampere-hours per pound) is 3 1/2 times higher than that of zinc.[28] For weight critical applications such as the floating OTEC platform, it is recommended that commercial aluminum anodes be used. These contain a nominal 0.045-percent mercury, which means their environmental impact will also have to be assessed.

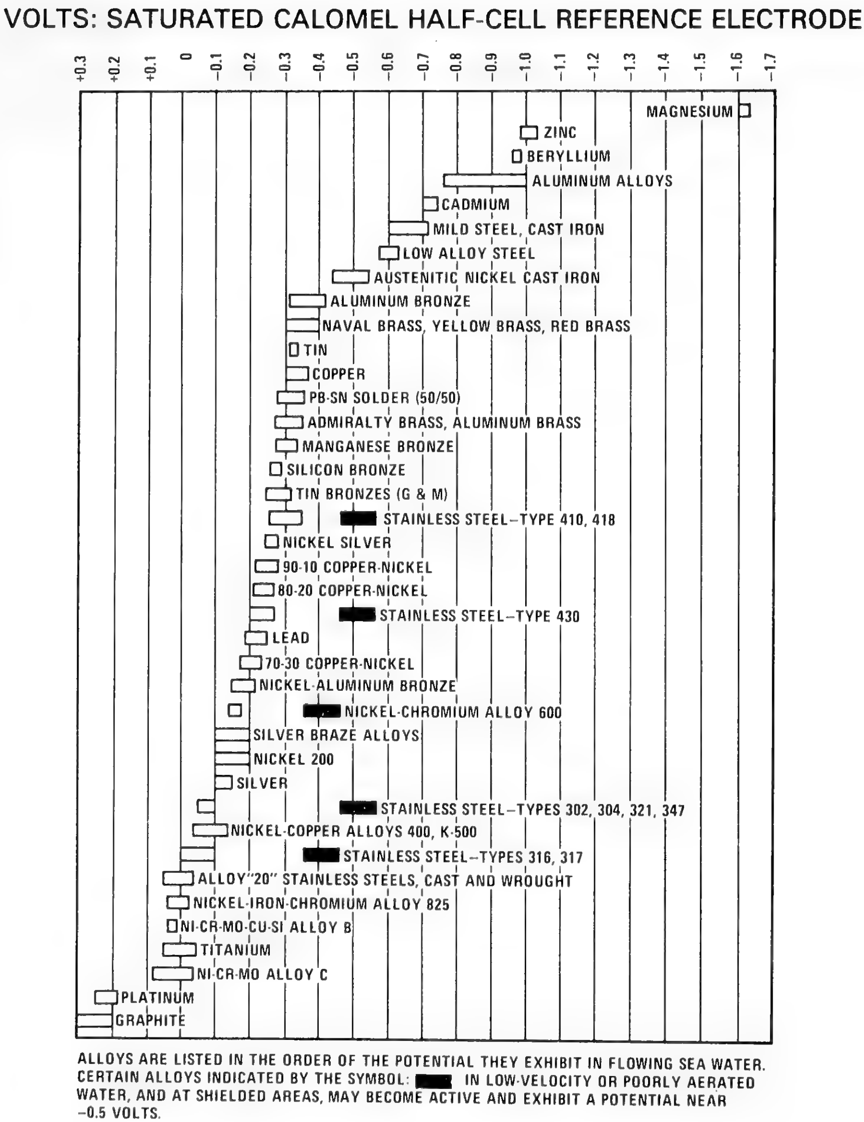


Figure 5 - Corrosion Potentials in Flowing Seawater (8 to 13 ft/s), Temperature Range 50° - 80° F (from reference 27)

TABLE 3 - DESIGN CRITERIA FOR CATHODIC PROTECTION SYSTEMS

| Production Area | Environmental Factors* | | | | |
|---|---|---|---|---|---|
| | Water Resistivity (ohm-cm) | Water Temperature ($^{o}$ C) | Turbulence Factor (Wave Action) | Lateral Water Flow | Typical Design Current Density (mA/ft$^2$) |
| Gulf of Mexico | 20 | 22 | Moderate | Moderate | 5-6 |
| U.S. West Coast | 24 | 15 | Moderate | Low | 7-8 |
| Cook Inlet | 50 | 2 | Low | High | 35-40 |
| North Sea | 26 | 12 | High | Moderate | 8-15 |
| Persian Gulf | 15 | 30 | Moderate | Low | 7-10 |
| Indonesia | 19 | 24 | Moderate | Moderate | 5-6 |

*Typical values and ratings based on average conditions, remote from river discharge.

A 4000-ft steel cold water pipe will be difficult and costly to protect and maintain. The pipe is not a replaceable item and will require cathodic protection during its service life. Anode weight will probably preclude a sacrificial anode system and require the use of impressed current. However, problems such as repair depth and high internal resistance drops in long anode leads will require special design to minimize maintenance requirements and guarantee adequate protection.[29] The number, type, current capacity, and location of exterior anodes on either modules or the cold water pipe will depend greatly on the physical configurations of each component. Shape will strongly influence current and potential distribution from the anodes.[30]

In the OTEC application, the proposed aluminum heat exchangers will be anodic to both steel and bronze components in the pump housing and impeller. Additionally, copper ions from the freely corroding bronze will deposit on less noble heat-exchanger surfaces and cause accelerated attack of the aluminum by the heavy-metal ion displacement effect. It is imperative that these thin-walled heat-exchanger tubes not be subjected to any galvanic attack. The galvanic relationships would be reversed if titanium heat exchangers were used; steel components would be anodic and would

corrode sacrificially. The methods for precluding galvanic attack in both cases are the same - decouple the galvanically incompatible materials by "electrical isolation techniques" or use cathodic protection. "Isolation techniques" include coating cathodic components to minimize their galvanic effects on less noble components and isolation of incompatible materials (viz, using a nonconductive pipe section between steel piping and the heat exchangers).

Cathodic protection is attained by shifting the portential of the most cathodic element to a point near the potential of the most anodic metal in the couple. Under these conditions there will be no active galvanic couple. If all parts are protected at the protective potential for the most anodic element, local galvanic cells are stifled, and even general corrosion virtually is eliminated. The protective potential of a metal is usually 100 to 200 mV more negative than its freely corroding potential.

If reinforced concrete is used for the cold water pipe, the feasibility of applying cathodic protection to steel rebars should be investigated. While cathodic protection has been applied in some cases to rebars in bridge applications, it is common practice to permit the bars to corrode freely. The alkaline conditions in concrete reduce steel corrosion rates and consequently the current requirements for cathodic protection.[31]

Metal strainers used to prevent particulate or foreign object intrusion into the piping system probably will require impressed current protection. The protective current requirements will be high due to large surface areas and inherent turbulence.

In general, it is difficult to design a cathodic protection system for a structure before its final configuration and location are decided. However, the design considerations listed above can be used to determine current requirements and the type of cathodic protection system necessary. It is important that the need for cathodic protection be recognized, and that weight and cost considerations be included early in overall OTEC design criteria.

## Coatings, Cathodic Protection, and Corrosion

Although coatings are discussed separately, two factors effecting materials compatibility should be addressed. First, while painting

exposed metal surfaces reduces the current capacity required for cathodic protection, current requirements will increase as deterioration of the paint progresses. (Also, some generic types of paints (e.g., coal tar epoxy) are better insulators than others (e.g., vinyl) and will require less current capacity.) Second, copper metal or cuprous-oxide-based antifouling paints can accelerate corrosion of steel and induce heavy-metal deposition attack of aluminum surfaces. While an organotin-type antifoulant would be preferable to reduce the possibility of accelerated attack, it may pose some ecological concern.

## ANTICORROSION COATINGS

Anticorrosion paints generally are classified as _multicomponent_ and _single package_ types. The former contain at least two components which react chemically and irreversibly to form a thermosetting film. The latter form films initially by solvent evaporation and subsequently cure to achieve greater film integrity through chemical and/or physical changes, e.g., oxidation and polymerization. The multicomponent coatings have been found to be the most protective for steel and other corrodible metals.

### Two-Component Epoxy Paints

Amino-group-reacted epoxies have been established as the best anti-corrosion paints for marine use. These paints, in the wet state, will displace residual loose dirt, oil, and water which are sometimes found on metal surfaces under industrial conditions.[32] The applied polyamide epoxy paints adhere and perform much better than other paints which are less tolerant of moisture or other surface contaminants.

For cathodically protected surfaces, a highly alkali-resistant epoxy, such as coal-tar-reacted epoxy catalyzed with a low molecular weight amine, is more resistant to the alkaline conditions at the cathode.[33] Therefore, amine-reacted coal tar epoxies are recommended in lieu of epoxies reacted with amide for high potential (1.1 V) cathodically protected surfaces.

### Single-Component Paints

The single-component paints proven for marine construction are those based on vinyl and chlorinated rubber.[34] Occasionally, proprietary single-

component paints are found to vary in performance from batch to batch. Consequently, they should be comparison-tested with recommended Government specification coatings before they are considered for use. Some of these Government specification coatings will be identified in the latter part of this section.

### Zinc-Rich Primers

In new construction, such as an OTEC power plant, preconstruction primers are generally used on all steel members before assembly.[35-37] These primers are thin, but adequately protect steel plate. When the steel structure is completed, the primer, generally a zinc-dust coating, usually is overcoated with another zinc-rich primer coat followed by an epoxy anticorrosion paint. Therefore, the final paint system becomes a zinc primer overcoated with an epoxy coating to form a combination system. Often, when the zinc coating is damaged in construction, it is touched up with a fresh zinc coating. Typically, the best performing zinc-rich paints utilize the inorganic silicates.[38-40]

### Anticorrosion Coatings Systems for Steel and Titanium

Three Government specification paint systems are recommended for the general protection of steel from corrosion attack in the seawater and OTEC power plant environment. These are coal tar epoxy, polyamide epoxy, and the zinc-rich primer in conjunction with an epoxy. These materials are listed in Table 4 and are available from commercial sources.[41] There is also a compositional specification which covers a Navy-formulated polyamide epoxy paint system.[42] While titanium does not require anticorrosion coatings, epoxy paints may be used as undercoats for subsequent antifouling paints.

### Anticorrosion Coatings for Aluminum

Aluminum is more reactive than steel. It requires more chemical treatment than steel for resisting corrosion.[43,44] To obtain a durable coating on aluminum, the primer must contain passivators such as chromates. There are two paint systems recommended for aluminum: one a polyamide epoxy, and the other a vinyl primer system. These are listed in Table 5.

TABLE 4 - ANTICORROSION COATINGS FOR STEEL

| | Coating System 1 | Coating System 2 | Coating System 3 | Coating System 4 |
|---|---|---|---|---|
| | Coal Tar Epoxy System | Polyamide Epoxy System | Zinc-Rich Primer/ Polyamide or Coal Tar Epoxy | Epoxy/Primer Neoprene Erosion Resisting Coating |
| Cost/Ft$^2$ | \$0.15 | \$0.17 | \$0.24 | \$1.00 |
| Lifetime | 5 yr | 5 yr | 6 yr | 6 yr |
| Effectiveness | Best system for cathodic protection | Best system for less than properly prepared surface | Best system for non-cathodic protection | Best system for resisting cavitational erosion |
| Environmental Impact | None | None | None | None |
| General Description | Two-component black paint | Two-component light color paint | Two-component dark color paint | Two-component paints green epoxy primer and black rubber coating |
| Availability | Commercial product | Commercial product | Commercial product | Commercial product |
| Application | Conventional spray | Conventional spray | Conventional spray | Special spraying technique with conventional gun |

TABLE 5 - ANTICORROSION COATINGS FOR ALUMINUM

| | Coating System 5 | Coating System 6 |
|---|---|---|
| | Strontium Chromate Epoxy System (DTNSRDC Formula 1112) | Zinc Chromate Vinyl System (MIL-P-15328 and MIL-P-15930) |
| Cost/Ft$^2$ | \$0.17 | \$0.18 |
| Lifetime | 4 yr | 3 yr |
| Effectiveness | Best system for freshly prepared surface | Best system for general use |
| Environmental Impact | Very slight chromate escape | Very slight chromate escape |
| General Description | Conventional two-component paint | Combination of one- and two component paints |
| Availability | Commercial product | Commercial product |
| Application | Conventional spray or roller | Conventional spray |

Some proprietary vinyl systems are available which perform just as well. To date no other epoxies have shown performance equal to the systems listed.

## Surface Preparation

Steel. The most satisfactory method of preparing the steel surface for painting is abrasive blasting,[45,46] which removes all rust, mill scale, and foreign matter. Grains of abrasive hitting the surface provide a beneficial surface work hardening and produce no known detrimental metallurgical changes. The resultant surface profile of 2 to 4 mils gives a "tooth" to which the coating adheres. In the present environment of strict pollution control, open blasting may soon be restricted to the use of nonsiliceous abrasive. If open blasting is forbidden, then parts must be (shot) blasted in shops during the fabrication stage. For OTEC, both methods are recommended. It may be feasible to use a nonblast method of surface preparation, but this should be thoroughly evaluated before it is specified.

Aluminum. Aluminum also is prepared for painting by abrasive blasting. The ideal abrasive is aluminum oxide, which is very expensive. Substitute abrasives may be used provided that surface cleanliness and suitable profiles are maintained. The recommended profile after blasting is 1 to 2 mils. Aluminum must be painted within 24 hr of blasting. The blasting surface must be protected from moisture and foreign matter during this period.

## Recommended Practice for OTEC Plants

Warm or Cold Water System. The warm or cold water system can rely on both types of anticorrosion coating systems, depending on the length of corrosion protection desired. Areas which are inaccessible to renewal for periods greater than 5 yr will be best presevred with a combination of cathodic protection and coal tar epoxy coatings. For parts which can be brought in for overhauls more frequently, standard single-part anticorrosive coatings in combination with impressed current will provide adequate preservation.

Pumps. Generally, moving parts are difficult to protect because metals in moving systems are usually galvanically active due to increased diffusion of oxygen and removal of protective layers which would otherwise prevent local cell corrosion currents. However, in one centrifugal pump design, the impeller is coated with a neoprene coating.[47] This should reduce galvanic currents as well as reduce cavitation erosion of the blades. This type of coating is recommended for either a steel or titanium blade. Other moving parts must also be coated wherever possible to prevent production of excessive galvanic currents. The Navy has developed a neoprene coating which is listed in Table 4. The nonmoving parts of the pumps that are exposed to seawater also can be protected with the same coatings.

Housing. The housing will be moored at sea for periods up to 10 yr and therefore will require high-performance anticorrosive coatings, such as epoxies, for all steel parts.[48,49] Cathodic protection is also necessary.[42,50,51] Light metals, such as aluminum parts, fixed to the platform must be protected with both a proper coating and a cathodic protection system.[52] Corrosion potential electrodes and probes should be located on critical metal structural components and should be checked by periodic underwater inspection.[53]

The power modules that can be detached and towed back to a repair station every 2 yr will be protected adequately by procedures well known to the marine construction and ship maintenance industry.[52,54] These will not be given in detail, but can be found elsewhere.[55,56]

Summary

Two-component anticorrosion paints are recommended in lieu of one-component paint, although vinyl and chlorinated rubber are suitable single-component coatings. The two-component paints highly recommended are polyamide epoxy and coal tar epoxy. The former is a universal coating, and the latter is suitable for areas of high cathodic potential. Zinc-rich paints are also suitable as preconstruction primers.

In selecting anticorrosion paints, an extremely important factor is the compatibility of the paints with other paints in the system, i.e.,

primers, antifoulants, and tie-coats. In this report, specification recommendations should be strictly observed.

Epoxy paints in general are recommended for all parts of the plant except for flexible surfaces. Highly resistant metals, such as titanium, may not require corrosion protection by painting, if properly isolated from other metals and if antifouling protection is not needed. For the pumps, neoprene coatings are recommended in areas of high erosion. Aluminum surfaces must have a tested, chromate-containing primer.

Good surface preparation prior to painting is required, and abrasive blasting is recommended. Steel must be abraded to a coarser finish than aluminum; either should be painted almost immediately after blasting.

FIBER-REINFORCED PLASTICS

One candidate material for the OTEC power plant cold seawater pipe is fiber-reinforced plastic (FRP). A single large FRP pipe has been proposed[8] to provide the quantity of cold seawater necessary for the operating requirements of the power plant. The pipe could be manufactured in 60-ft lengths, and the total length of the pipe might extend to 4000 ft.

FRP is a generic term which refers to organic matrices reinforced with fibrous materials. The low-cost, high-strength characteristics make glass the most widely used fiber in fabrication of FRP structures, and the information contained herein is based on the use of glass fiber as the reinforcing material. The important resins utilized are polyesters, epoxies, phenolics, and furanes.

Two grades of glass are used: "C" and "E." C glass (chemical grade) is treated to increase its resistance to acid and chemical attack; it is normally used as the surfacing veil or inner liner of equipment. E glass (electrical grade) is applied over the C glass inner liner to build strength into the structure. The strength of FRP structures is a function of glass content.

Large FRP structures are manufactured by a hand lay-up or a filament-winding process. In a typical hand lay-up method, a mandrel is coated with resin, and C glass is embedded in the resin to obtain a resin-rich inner layer of specified thickness. Additional layers of resin and resin-impregnated E glass mats are applied over the inner layer to build strength

into the structure. During construction, the reinforcing mats or fabrics are overlapped or oriented to provide adequate distribution of stress and to give uniformity to the cross section of the structure. In the filament-winding process, continuous strands of resin-impregnated glass are wound onto a mandrel. Inner layers are commonly resin-rich. Large-capacity (up to 280,000 gal.) storage tanks have been constructed by a form of multiple-strand winding,[57] and large-diameter piping (9 to 13 ft) has been manufactured for power plant cooling and sewage systems. Pope[58] describes the manufacture of a 9-ft-diameter pipe for a conductor circulating water system of a 325-MW electric power plant. The pipe was manufactured by using a 65-degree filament helix angle overwind and a dual resin system consisting of a 100-mil-thick inner layer of a flexible bend polyester resin and an isophthalic resin for the structural wall to give a minimum wall thickness of 1 1/8 in. The pipe was fabricated in 50-ft sections; 60 field joints were required to assemble 2500 ft of pipe. Cheetham[59] lists some of the advantages and limitations of the use of FRP in the marine environment.

Some FRP advantages are:

1. Corrosion free in seawater
2. High strength-to-weight ratio
3. Resistant to marine biological attack (borers, etc), but will foul.

Some FRP limitations are:

1. Low elastic modulus; deflections could be unacceptably large and elastic instability must be monitored.

2. Does not flow plastically when its elastic limit is exceeded. Failure occurs by resin fracture and disruption of the glass/resin bond. Although FRP is capable of absorbing about four times as much strain energy as steel in its elastic range, the capacity of steel to absorb an enormous amount of extra energy by plastic deformation is absent in FRP.

3. Absorbs and transmits water (but with resins suitable for marine use, correctly postcured, the amount is insignificant). Water absorption causes loss of strength by hydrolyzing the glass filament surfaces and by disrupting the glass/resin bond. The correct surface finish applied to the glass(chemical treatment which enables the resin to bond chemically to

the glass) resists this attack and is all-important in maintaining strength under prolonged immersion.

## Durability

Fried and Graner[60] discuss the utilization of glass-reinforced plastics (GRP's) in marine structural applications. Information is given on the durability of a large reinforced plastic structure, a submarine fairwater (sail), after 11 yr of service. The sail was a 1/4-in.-thick reinforced plastic laminate fabricated of a high-strength glass cloth. The cloth was a satin woven bidirectional textile treated with a special finish to improve resin bond and water resistance. The plastic matrix was a general-purpose room temperature curing polyester resin, blended with 10 percent of a flexible resin for increased toughness. It was manufactured by a conventional vacuum-bag molding process which resulted in a high-quality laminate having a high glass content and a void content of less than 1 percent. The data obtained after the 11-yr exposure, Table 6, show that the mechanical properties of the GRP material did not differ substantially from the original.

TABLE 6 - EVALUATION OF GRP FAIRWATER AFTER 11 YEARS OF SERVICE

| Property | Condition | Original* Value | After Exposure Panel 1 | After Exposure Panel 2 | After Exposure Average |
|---|---|---|---|---|---|
| Flexural Strength, psi | Dry | 52,400 | 51,900 | 51,900 | 51,900 |
| | Wet** | 54,300 | 46,400 | 47,300 | 46,900 |
| Flexural Modulus, psi x $10^6$ | Dry | 2.54 | 2.62 | 2.41 | 2.52 |
| | Wet | 2.49 | 2.45 | 2.28 | 2.37 |
| Compressive Strength, psi | Dry | Not determined | 40,200 | 38,000 | 39,100 |
| | Wet | Not determined | 36,000 | 35,200 | 35,600 |
| Barcol Hardness | Dry | 55 | 53 | 50 | 51.5 |
| Specific Gravity | Dry | 1.68 | 1.69 | 1.66 | 1.68 |
| Resin Content, % | Dry | 47.6 | 47.4 | 48.2 | 47.8 |

*Average of three panels.

**Two-hour boil.

GRP in seawater will foul. Basil[61] found no damage to GRP panels exposed 14 months in seawater. In quiet seawater, the panels were good collectors of marine organisms. The fouling was removed easily by scraping, and there was no evidence of attack by marine borers or other marine life. Drilling platform operators report no fouling problems in 12-in.-diameter seawater circulating lines operating continuously for approximately 5 yr at maximum velocities of 5 ft/s, but fouling does occur when the lines are shut down. Generally, the magnitude of fouling of GRP piping is less than for some of the metallic piping materials. The reduced fouling has been attributed to the smooth interior pipe walls which provide a poor surface for firm attachment of marine life. Detailed analysis of fouling on GRP is presented later.

### Summary

GRP materials are inherently corrosion-resistant in the marine environment. Long-time exposure to seawater does not appreciably degrade the physical properties of material. Marine fouling growth occurs but may be removed. Maintenance problems are expected to be minimal. Problems may arise during manufacture since nothing this large has ever been constructed using GRP. Manufacturers are confident that such units are possible with the current state of the art.

## FOULING - OUR REAL PROBLEM

Fouling is a general term which encompasses the attachment of soft-bodied or hard-shelled marine organisms and the physical agglomeration of organic and inorganic matter to a surface. However, in our context, fouling generally refers to living plants and animals only. Any unprotected marine structure will foul with the maximum accumulation occurring in the photic zone which extends to about 500 to 600 ft deep. From 500 to 600 ft to about 1500 ft, there is a dramatic decrease in fouling. Below 1500-ft depths to the bottom, fouling is so scarce that often it cannot be measured.[62-66] Although this is true for gross fouling, microfouling (slime) is found all the way to the bottom in decreasing degree.[63,66,67] Both micro- and macrofouling can be considered insignificant below 2500 ft (approximately 4000 ft in tropical waters).

In the photic zone, the first "fouler" can be either bacteria and/or diatoms (depending on geographical location).[64,67] The normal temporal sequence is: (1) bacteria, bacteria and diatoms, or diatoms and protozoa; (2) sessile microorganisms (bacteria and/or diatoms); (3) colonial microorganisms; and (4) macroorganisms.[68] The initial step varies from location to location, even if only a few miles apart. There have also been some cases where the barnacles have been the "pioneer" species. The organisms will begin to attach readily only after the concentration of organisms on a surface is much greater than that of the surrounding water.[69,70]

Within the photic zone, a stratification is set up, especially in calm waters. In the Central Pacific, about 4 to 5 miles offshore, in the top 300 ft it is something like this:[71]

1. Calcareous Zone with barnacles, anemones, etc
2. Algae Zone with ulva, other green algae, and red algae
3. Free Zone, just below the Algae Zone
4. Lower Zone with tubeworms, hydroids, bryozoa, etc.

Although the bacterial population on a surface decreases with depth, bacteria are found to the bottom, no matter what the depth.[66,67,69,72] This microbial growth is reponsible for the establishment of the fouling community under relatively adverse conditions because it: (1) attracts the larvae of foulers, (2) serves as a food source, and (3) passivates inhospitable surfaces.

The decrease of fouling with depth and distance from shore does not appear to be influenced by any single environmental factor.[63,66] Probable factors include: (1) decreased water temperature, (2) lack of organic matter (food), (3) currents, and (4) available attachment surfaces. Any of the above can become limiting; i.e., there may be enough organic matter in the water for sustenance, but there may be few solid surfaces available for attachment. Thus, the presence of fouling organisms (especially of larvae) in that region would be limited. With decreasing fouling as a function of depth and as distance from shore increases, there is a concurrent decrease in the speciation;[63,72,73] i.e., as bryozoans increase in numbers, the barnacle population decreases. Since the bryozoans and/or hydroids are usually smaller than barnacles and/or mussels, the total biomass attached will decrease.[68] Predominant open ocean fouling organisms

are hydroids (from surface to bottom in decreasing numbers),[69,72] gooseneck barnacles (from surface to 3 to 4000 ft), mussels (only to about 30 miles offshore and down to about 100 ft), tunicates (in warm waters down to about 500 ft), and bryozoans (surface to bottom increasing in numbers with depth). This decrease in quantity and species diversity has been encountered in inshore waters.[72] In the Gulf of Mexico, the biomass decreases from 4175 g/m$^2$ at the surface to 84 g/m$^2$ at the bottom (10 ft) within a few hundred feet of the Louisiana shore.[72] Similar data have been obtained in the Pacific and in the Atlantic. This relationship is quite dramatic in the Tongue of the Ocean (off Bermuda). Figure 6 shows that fouling was about 1000 g/m$^2$ at the surface, and it declined gradually to 0 by 800 to 900 ft.[74]

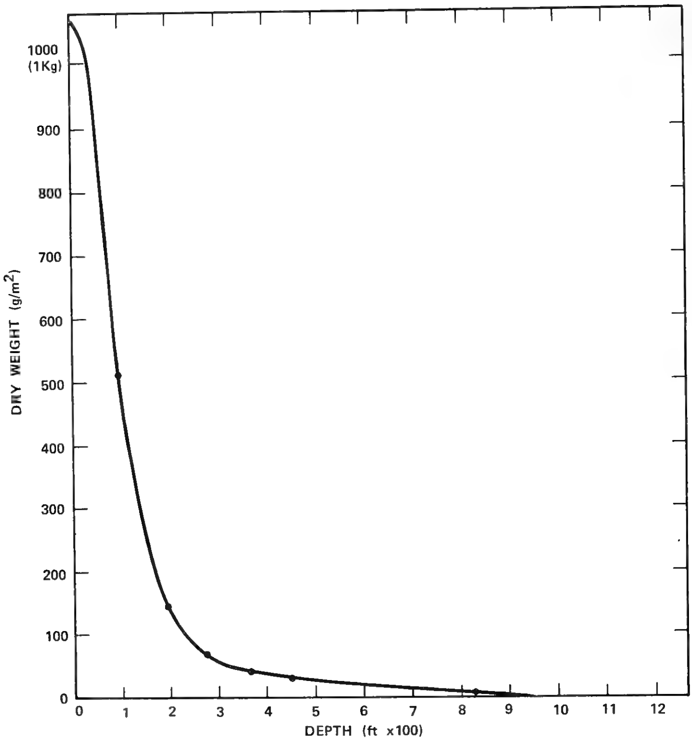


Figure 6 - Biofouling Mass as a Function of Depth in the Tongue of the Ocean[74]

There usually are no hard-shelled forms below the photic and/or mixed layer zone (Figure 7).[71,74] Table 7 lists general relationships between depth and geographic location for some fouling organisms. Marine borers were found attached on "all" surfaces at various depths (down to 7000 ft) in protected areas away from water currents. These borers have been known to bore into materials which were "unborable," e.g., lead, concrete, etc.[63,68,72]

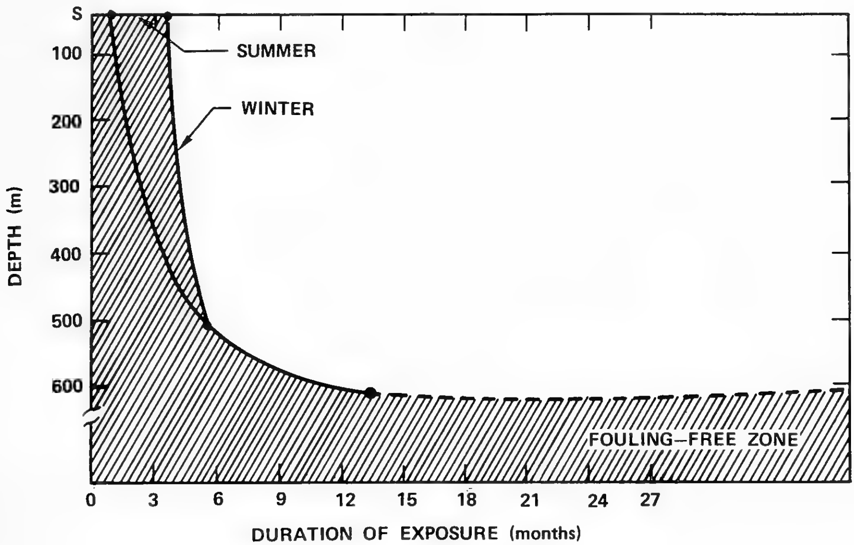


Figure 7 - Time to Reach Hard-Shelled Fouling Stage as a Function of Depth

The most generally accepted boundary for "insignificant fouling" is 65 miles offshore.[72] At this and greater distances, the fouling, although present and often bothersome, is reduced to manageable levels.[72] Not only is the quantity lessened, but also the species diversity is small;[72] an antifouling system could be less complex as it would need only a narrow spectrum toxin.

TABLE 7 - HABITATS OF FOULING ORGANISMS

| Organism | Depth (General Maximum) (ft) | Range of Ocean |
|---|---|---|
| Hydroids | Surface to bottom (8-900) | All over |
| Gooseneck Barnacles | Surface to 500 ft (200) | Open ocean only |
| Mussels | Surface to 100 ft (30-50) | Shore to 30 miles |
| Starfish | Surface to 8,000 | All over |
| Snails | Surface to 10,000 | Especially in Pacific |
| Bivalves | Surface to 14,500 | Especially in Pacific |
| Tubeworms | Surface to 16,500 | Coastal waters |
| Sea Urchin | Surface to 16,000 | All over |
| Sponges | Surface to 600 | Coastal waters |
| Bryozoans | Surface to 900 (600) | All over (coastal waters) |
| Tunicates | Surface to 500 | All over |
| Borers | Surface to bottom (7,000) | All over |
| Jellyfish | Surface to bottom | All over |
| Fungi | Surface to 600 | All over |
| Acorn Barnacle | Surface to 500 (100) | Coastal waters (all over) |

Fouling affects a structure in many ways, depending on its composition and severity. Generally, effects of fouling are: (1) increased weight (as much as 20-25 $lb/ft^2$); (2) increased drag, which strains mooring lines; (3) increased cost and time for onsite modular assembly and disassembly; and (4) increased corrosion and deterioration (not only the formation of metal oxides, but flaking or powdering of concrete).[75] Many of the side effects of fouling on concrete surfaces could be eliminated by paint films properly applied and of sufficient thickness to reduce porosity. Paint systems composed of very thick (8- to 12-mil) antifouling paint films applied on zinc and copper sprayed base coatings have protected many different metals in deep waters.[76] Along the surface in the middle of the Atlantic Ocean, toxic surfaces remained fouling-free for longer periods of time than those close to shore.[69] It is also possible that the leaching rates for antifouling paints may decrease with increasing depths. However,

depending on the location and depth, fouling can occur on "toxic" surfaces. Certain experts believe that, since the organic content of the water is very low, any surface with concentrated organic compounds would foul, even if these organic compounds are toxic.[69,74]

High biomass and fouling density on surfaces provide food for grazing fish. Therefore, an OTEC platform may play a beneficial ecological role as an artificial reef.[74] It is known that some fish can cause much structural damage. Sharks can bite through metal cables in the process of "testing" their teeth, and certain types of fish have solid plates for lips and cause much damage while grazing.[75] Invertebrates such as starfish can grind holes on various surfaces.

## ANTIFOULING COATINGS

There are four approaches in the use of biocidal layers to prevent sea-growth fouling: (1) coatings, (2) sheet materials, (3) impregnates, and (4) toxic metal sheathing. These materials and approaches are discussed in descending order of their frequency of use.

### Coatings

Antifouling coatings can be categorized as those containing: (1) low toxicity ingredients, such as cuprous oxide; (2) medium toxicity ingredients, such as organotin; and (3) high toxicity ingredients, such as arsenic, lead, and mercury.[77-79]

Cuprous oxide paints are established materials with a long history of excellent performance, have little known adverse effect on the marine ecology, and are widely available as commercial formulae or specification paints.

Organotin-containing paints are at least as effective as copper-based paints in most uses. However, because organotins are more toxic to marine creatures and man than inorganic copper compounds, they require greater care and expense in application, removal, and disposal.[82] Environmental considerations of these materials in the marine ecosphere are under study.

Antifouling paints have been made with other antifoulants. Restrictions on their application result from their toxicity to humans and effects on the marine environment. Very toxic, although highly effective, paints,

such as those containing mercury, trialkyllead, arsenic, and other chemicals, have been made and used.[82] However, today's environmental protection restrictions discourage common usage; they could not be justified for use on an OTEC plant.

### Antifouling Sheet Material

The first practical antifouling sheet material was manufactured by the B. F. Goodrich Company and called "No-Foul." The material is an 80-mil-thick black neoprene rubber impregnated with tributyltin oxide (TBTO).[83,84] Due to the large amount of antifoulant in the No-Foul sheet, its service life is much longer than 4 mils of typical antifouling paint.[85]

### Impregnants

Antifoulants have been used to impregnate the outer surfaces of concrete and wooden pilings. There is no practical way to restore the antifoulant when it is exhausted. This limiting toxic content also occurs in paints or sheet-type coatings. Ecological concerns would depend upon the nature of the impregnant used.

### Toxic Metal Sheathing

Copper metal and its alloys have been used for fouling prevention in spite of their limited effectiveness. Some drawbacks for its use are: (1) the sheets are difficult to form and attach on highly curved surfaces and (2) galvanic corrosion problems occur when the sheets are not isolated from other metals. Recent work employing plasma spray techniques to apply copper metal and alloy powders to nonmetallic substrates has eliminated forming and attachment problems; however, continued effort is required to assess the long-term performance of this new technique. Environmental considerations would be minimal with this approach.

New Antifouling Systems

Multiple Antifouling Paints. Some new commercial antifouling paints incorporate a mixture of antifoulants. Commonly, tributyltin fluoride (TBTF) is mixed with cuprous oxide in the newest proprietary products.[86,87] Although the cost of mixed antifoulant coatings is higher, their performance exceeds that of the mono-antifoulant paints. While there is no U.S. Government specification defining a multiple antifoulant paint, such development is under way.

Organometallic Polymer Paint. A new approach to incorporate antifoulants in paint is by chemical combination of antifoulants to a polymer backbone which then serves as the paint resin.[88,89] The antifoulant is released in seawater as to polymer dissociates. A research group at the David W. Taylor Naval Ship Research and Development Center is synthesizing these polymers and preparing coatings with them. Researchers in foreign countries, such as Japan, Australia, England, etc, have also been very active in developing organometallic polymer (OMP) paints.[88,89] Other uses, such as impregnants for concrete and other materials, are also being pursued. Although the cost of OMP coatings will be 20 to 50 percent higher than that of non-OMP paints, their performance may justify their use.

Ablative Coatings. A new organometallic polymer coating (self-polishing copolymer (SPC)), having a low pirment content, ablates in flowing water, thus generating a self-smoothing effect. This material has not had enough usage to prove or disprove the claims made by the vendor (International Paint Company); it may be relatively ineffective for stationary structures. Its cost is greater than that of conventional paints by 50 percent or more.

Paints Containing New Antifoulants. New biocides and growth regulators which are environmentally acceptable are being examined as antifoulants and are being developed at an accelerated pace. A successful candidate

screened from among many by DTNSRDC was 2,4,5,6-tetrachlorosiophthalonitrile, known commercially as Nopcocide N-96™. It has been formulated into a neoprene base for making successful antifouling coatings and structural rubbers. Its use should be acceptable by regulatory agencies as many environmental tests have been performed on Nopcocide N-96 for other uses. Cost, availability, and environmental impact should not be a problem. However, further development is required to produce acceptable formulations for extended use and to determine their influence on the corrosion of various metals.

Nontoxic Paints. The development of paints that repel sessile animals and paints formulated without toxic chemicals has been the goal of many biologists.[89] However, physically repelling surfaces that are practicable have not yet been disclosed.

Recommended Coatings

Cuprous Oxide Paints. *Copper-base paints are recommended for use only in the absence of aluminum parts and structures in an OTEC plant. Copper ions will accelerate corrosion of most marine aluminum alloys; this precludes the use of any copper antifouling paints in their presence.*

The Navy vinyl antifouling paint, Formula 121, MIL-P-15931, is recommended as the standard coating for all steel and other metal surfaces.[85,90] The paint is available at reasonable cost as a Government compositional specification item which precludes ingredient substitutes. Commercial cuprous oxide paints are also available and may be acceptable, but their performance must be verified and should be compared to the Government specification paint. Pure cuprous oxide paint can be handled by painters and maintenance personnel with a minimal amount of protection. The paint is packaged in conventional cans and used, as well as stored, like any other paint. Proprietary compositions of cuprous oxide paint are

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made in other bases than vinyl, with chlorinated rubber being the most common. These paints must be used over primers recommended by the manufacturer.

Another recommended cuprous oxide paint is Navy polyisobutylene antifouling paint, Formula 134, Military Specification MIL-P-22299.[91] This is a specialty paint which is highly flexible and performs well over rubber surfaces. It also can be used on rigid surfaces, although the standard vinyl paint would be slightly better. Cuprous oxide paints with other added antifoulants, such as tributylin fluoride, are common in proprietary products. These additions make the paint more toxic and, therefore, more effective to a wider range of fouling organisms. However, precautions required during its application result in increased costs.

Organotin Coatings. Two types of organotin coatings are recommended: Navy proposed Formula 170 (DTNSRDC Formula 1020A) and antifouling rubber sheeting, such as B.F. Goodrich Company's No-Foul sheet. Formula 1020A contains TBTO and TBTF physically combined in a vinyl base. It is a single package paint which can be rolled, brushed, or sprayed. Its toxicity is not high, but safety measures must be observed in its application, removal, and disposal.[92-94] The raw materials are readily available; the composition can be made by any marine paint manufacturer, and it can be stored. Proprietary organotin paints are also available, although most proprietary paints contain both tin and copper.[95] Some of these perform as satisfactorily as Navy paints. For OTEC use, an organotin paint should be specified for use over aluminum parts. Proprietary paints containing copper or any other materials corrosive to aluminum should not be used.

The second organotin coating recommended is an antifouling rubber sheeting called No-Foul™. It is 0.080 in. thick and is used as a cemented covering over underwater bodies to prevent fouling. The initial cost is high, and it requires significant labor to fit the material to the shape of the area to be covered. First an adhesive is sprayed on the substrate in substrate in several coats, then the back of the rubber sheet also is

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covered with cement. When ready to apply, the dried cement is "tackified" with solvent, and the sheet is hand rolled onto the surface. The hand rolling is needed to ensure adhesion. After rolling, the edges of each piece are trimmed to give a fairly uniform coating. The material together with its application is several times costlier than paint. However, where a longer-lived antifouling coating is required, such as in warm water inlet ports, this antifouling sheeting is recommended.

System and Material Identification Interrelationships

Warm Water System. The 26° C (79° F) seawater flowing through the warm water pipe at 1.2 m/s (4 ft/s) will create an environment conducive to fouling.[95] The concrete platform surfaces and all the metal surfaces in contact with the warm water inlet and outlet and which are amenable to periodic refurbishment will require a good antifouling coating, such as a heavily loaded organotin rubber sheeting. The trash grating protecting the inlet opening will also benefit from an antifouling coating. The grating and the inlet and outlet surfaces should be mechanically cleaned on a fixed maintenance schedule. In other areas, the choice of paint or sheeting will depend on the shape and force of water flow. The pump, valves, and pipes on the inlet and outlet sides of the heat exchanger will require organotin coatings, except in areas where water velocities in excess of 10 knots are encountered during operation. A second antifouling system, such as chlorine, will be required when these units are shut down.

Cold Water System. The cold water system will have 80° C (46° F) seawater flowing through at 1.2 m/s (4 ft/s). Because of the low temperature and very low depth source, the fouling character of this water will be weak, and the constant darkness in the cold water pipe will further inhibit growth. In addition, since refurbishment of any antifouling system can only occur when the whole power plant is dry-docked, it is recommended that no section of the cold water intake system need use antifouling coatings. For the cold water oulet all the recommendations for the warm water outlet will apply.

Fouling prevention will be unnecessary for the exterior surface of the cold water pipe. The master design[7,8] indicates that the OTEC plant should accommodate the increased weight (and decrease in buoyancy) due to fouling. Current plans are to tow the main platform to shore for refurbishment only after long periods of service.

With respect to the choice of materials for the cold water pipe, it should be noted that ordinary neoprene sheet fabricated over a steel frame design will not be protected from fouling, although No-Foul laminated over the structural neoprene sheet would prevent fouling for 3 to 5 yr. Sea animals have been known to damage rubber structures, such as surface ship sonar domes.

Pumps. If refurbishment on a 3-yr schedule is possible, the pumps can use antifouling materials that do not release copper ions downstream into an aluminum heat exchanger. Local flows in excess of 10 knots will prevent attachment of macrofouling organisms.

The stationary and slow-moving (less than 10 knots) parts of the pumps can utilize organotin coatings. This should be an absolute requirement of the warm water pumps and is recommended for the cold water pump.

Housing. One design[7] includes power modules that are separable from the platform proper. These modules, according to this plan, will be interchangeable and will be towed into a repair station for refurbishment. In this scenario, conventional paints which are very reliable for 2-yr periods can be renewed. Standard maintenance procedures for Navy and commercial ships can be adopted for these modules.[55,56] The platform stationed in the ocean for 10 yr would require a longer-life coating than any presently available.

### Commercially Available Antifouling Coatings

Coatings for Metal, Concrete, Plastic (GRP), and Other Rigid Surfaces. There are several types of antifouling paints which are recommended for rigid surfaces (Table 8). The cuprous oxide paint, such as Navy Formula 121, MIL-P-15931, can be applied over any rigid primed surface.[96]

TABLE 8 - ANTIFOULING COATINGS FOR RIGID SURFACES

| | Coating System 7 | Coating System 8 | Coating System 9 |
|---|---|---|---|
| | Navy Formula 121 (MIL-P-15931) Cuprous Oxide Paint | DTNSRDC 1020 (Specifications Being Prepared) Organotin Paint | Antifouling Rubber Organotin Sheeting |
| Cost/Ft$^2$ | \$0.40 | \$0.60 | \$3.85 including cement |
| Lifetime | 2 yr | 2 yr | 5 yr |
| Effectiveness | Broad spectrum | Broad spectrum | Broad spectrum |
| Environmental Impact | None | Very slight | Very slight |
| General Description | Conventional single package paint | Conventional single package paint | 80-mil-thick black rubber sheeting |
| Availability | Readily available | Made according to contracts | Proprietary product |
| Application technique | Sprayed or rolled | Generally rolled | Cut to size, cemented, and trimmed |

However, organotin paints, such as Navy Formula 1020A, must be used if aluminum is present in any structural capacity. Organotin antifouling sheeting material such as No-Foul, manufactured by B.F. Goodrich Company, also is recommended, particularly where longer service life is necessary. Greater detail on antifouling measures for GRP structures is available in a separate section.

Antifouling Coatings for Rubber and Other Flexible Surfaces. Rubber surfaces, such as neoprene, for the cold water pipe can be laminated with a flexible antifouling sheeting. It also can be painted with a flexible antifouling paint if it can be refurbished every 2 to 3 yr. These coatings are described in Table 9.

TABLE 9 - ANTIFOULING COATINGS FOR NEOPRENE

| | Coating System 10 | Coating System 11 |
|---|---|---|
| | Navy 134 Polyisobutylene AF Paint (MIL-P-22299) | Antifouling Rubber Organotin Sheeting |
| Cost/Ft$^2$ | \$0.40 | \$3.85 including cement |
| Lifetime | 2 yr | 5 yr |
| Effectiveness | Broad spectrum | Broad spectrum |
| Environmental Impact | None | Very slight |
| General Description | Conventional single package paint | 80-mil-thick black rubber sheet |
| Availability | Made to Government specification | Proprietary product |
| Application Technique | Sprayed | Cut to size, cemented, and trimmed |

Interrelationships Between Anticorrosion and Antifouling Paints. Anticorrosion and antifouling paints usually are selectded to provide a unified system with optimum compatibility and adhesion between the two coatings.[46-48] One example of this is the Navy vinyl antifouling paints applied over the Navy vinyl primer system. The former is the red Formula 121; the latter could be red lead Formula 119 or zinc chromate Formula 120. The polyisobutylene antifouling paint Navy Formula 134 used over the polyisobutylene black tie-coat Navy Formula 133 is another example of a compatible system.

The use of an antifouling paint over a foreign anticorrosive system frequently is possible. For example, Navy vinyl and Navy polyisobutylene antifouling paints can be applied over the Navy Formula 150-151-154 polyamide epoxy anticorrosion paint system with satisfactory results. However, certain other combinations may not be satisfactory. Information on the compatibility of one paint with another comes from experience and basic chemistry. Table 10 rates the compatibility of antifouling discussed here with certain anticorrosive coatings used by the Navy. Generally, compatibility is found between coatings of similar generic origin.

TABLE 10 - COMPATIBILITY OF ANTIFOULING COATINGS WITH ANTICORROSION PAINT SYSTEMS

| Anticorrosion Paint System | Antifouling Coating | | | |
|---|---|---|---|---|
| | Navy Formula 121 Cuprous Oxide Vinyl Paint (MIL-P-15931) | DTNSRDC Formula 1020 Organotin Vinyl Paint (No Specification) | Navy Formula 134 Cuprous Oxide Polyisobutylene Paint (MIL-P-22299) | Neoprene Rubber Sheeting with Organotin (Goodrich No-Foul) |
| Coal Tar Epoxy | Very good | Very good | Fair | Not recommended |
| Polyamide Epoxy | Very good | Very good | Fair | Not recommended |
| Coal Tar Epoxy Over Zinc Rich | Very good | Very good | Fair | Not recommended |
| Strontium Chromate Polyamide Epoxy | Very good | Very goof | Fair | Not recommended |
| Zinc Chromate Vinyl Primer | Excellent | Fair | Not recommended | Not recommended |
| Navy 133 Polyisobutylene Tie-Coat | Not recommended | Not recommended | Excellent | Not recommended |
| Cement and Primer System for Sheeting | Not recommended | Not recommended | Not recommended | Excellent |

Recommendation for Development

It is recommended that research and development be monitored to assess antifouling coatings of longer service life presently under development. These coatings may contain mixtures of antifoulant materials, but must be noncorrosive to aluminum if aluminum is selected for the heat-exchanger tubes. These coatings may be thick and may require special attention, such as periodic underwater maintenance. Environmental problems must be weighed. The complete antifouling system must be designed with redundancy to assure efficient operation for the OTEC plant. Since the warm water

inlet has the more severe requirements for fouling prevention, it can be assumed that results of research and development to solve this problem will solve lesser fouling problems of the OTEC plant.

## ANTIFOULING PROTECTION FOR FIBER-REINFORCED PLASTICS

The fouling of seawater piping systems is well documented.[73,97-100] This section addresses antifouling protection for fiber-reinforced plastics utilizing conventional and developmental antifouling coating systems as well as development of inherently antifouling FRP systems. FRP has been proposed for the cold water pipe for the OTEC power plant.[8] The use of FRP for the warm water intake screens of the power plant also is feasible. The recommendations for antifouling systems for these two components are based on the proposed designs as described in the Lockheed[7] and TRW[8] reports.

Requirements of antifouling protection for these two components will vary. Warm water intake screens will be the photic zone, whereas the cold water pipe may not.

### Current Antifouling Coating Systems

An antifouling coating would appear to be a feasible means of protecting an FRP cold water pipe. However, existing antifouling coatings have not been developed specifically for piping systems but rather for pleasure craft and Government and commercial ships. Therefore, application and expected service life of current antifouling coatings must be evaluated for their applicability to FRP pipe. This section only summarizes the matter of antifouling coatings since the subject has already been considered.

Ideally, the maximum service life of an antifouling coating ranges from 2 to 4 yr,[101] but in practice the service life of conventionally used antifouling coatings is shorter. Navy documentation indicates the antifouling effectiveness of copper-oxide-based antifouling coatings ranges from 3 to 18 months in tropical waters to 3 yr in temperate waters.[73] A limited study of commercially available organotin paints, which began in 1973, indicated that under static panel-exposure tests the antifouling service life of organotin paints may range from 2 to 7 months, depending

on the formulation.* On the average, the majority of organotin paints tested were effective for 12 to 18 months in temperate waters. Copper- and organotin-based marine coatings based on a variety of organic film-forming polymers are available. However, the coatings which give the best overall performance are formulated with vinyl-base polymers, chlorinated rubber, or epoxy resins.[101] Organotin antifouling formulations show the greatest promise as antifoulants effective against a broad spectrum of marine organisms.[101,102] These are generally based on tributyltin oxide, tributyltin fluoride, or triphenyltin fluoride (TPhTF). Copper and organotin antifouling coatings are commercially available.

The degradation of organotins in the seawater environment is not well defined. Studies by M&T Chemical Company indicate the mechanism is hydrolysis of the organotins in seawater.[103] Presently, studies are being performed by Dr. M. Good and Dr. L. M. Frenzel of the University of New Orleans to investigate the release mechanisms of organotin antifouling materials. In addition, Dr. F. Brinckman of the National Bureau of Standards has developed an analytical method which uses a combination of atomic absorption spectroscopy and liquid chromatography for the determination of organotins in very low concentrations. There is evidence that the organotins may decompose in seawater to inorganic tin,[103] but further studies are needed to verify this for tributyltin-containing compounds, especially those employed as antifoulants.

Most reinforced plastic structures are glass-reinforced. Other reinforcements for plastics include fibers of graphite, boron or metal, and natural and synthetic organics.[104] Many data exist for marine application of glass-reinforced plastics, specifically polyesters and epoxies, in small boat hulls, various ship appendages, sonar bow domes, and piping systems. Surface preparation of an FRP pipe prior to coating would follow practice that is standard for the given material and coating. For example, glass-reinforced plastic structures normally are sandblasted or sanded, rinsed with freshwater or solvent, and then dried thoroughly before painting. In general, a primer system is applied prior to the antifouling coating. Both are generally sprayed on.

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*Montemarano, J. A., DTNSRDC (Code 2865), personal communication.

## Summary of Current State-of-the-Art Coatings

Although it is technically feasible to provide antifouling protection by using coatings on the OTEC cold water pipe, only a 2- to 3-yr service life can be expected from the presently available commercial organotin- and copper-based coatings. This service life is insufficient for the planned use of the cold water pipe.

## Antifouling Techniques Under Development

Antifouling techniques under development which would be applicable for the FRP cold water pipe are: (1) long-lived antifouling coatings, (2) inherently antifouling FRP, and (3) antifouling liners.

Coatings. The use of existing antifouling coatings for the cold water pipe has been discounted due to short service life. However, Navy and industry are developing coatings with a longer antifouling service life.

Developmental coatings, expected to be commerically available in the early 1980's, are based on organotin polymers (resins) in which the antifoulant is chemically attached.[105] Ideally, release of the antifoulant to the marine environment is controlled. Expected service life is 5 yr.[77] Cost of coatings based on these resins is expected to be comparable to heavily loaded copper-based vinyl coatings. However, additional expense may be incurred in applying and removing organotin coatings due to their toxicity. The Research Organization of Ship's Compositions Manufacturers Ltd. (ROSCM) recommends that, during the application of organotin paints, a respirator be used with the filter in addition to the protective equipment recommended for use when applying copper-based paints.[103] The United States Navy has established guidelines for the safe application of organotin paints. Presently, organotin polymers are also being investigated by the Navy so that guidelines may be established for their safe handling.

Experimental antifouling coatings are not limited to organotin-polymer-based formulations. Extensive work has been performed in developing antifoulants based on organic compounds, other organometallic compounds, and organometallic polymers. Formulations based on other organic toxics include such compounds as diiodomethyl sulfone, 1,2,3-trichloro-4, 6-dinitrobenzene, pentacyclic amides and 2-(N,N-dimethylthiocargamyolthio)-

5-nitrothiazol,[106] pesticides such as DDT[106] and Nopcocide,[107] and juvenile hormones.[108] Organometallic compounds that have been evaluated as antifoulants include those of mercury, copper, tin, antimony, bismuth, and arsenic.[106] The development of organomercury and organoarsenic compounds is not being pursued due to environmental restrictions, although these compounds are effective antifoulants.[108] Patents which cover the use of organotin polymers as antifoulants are limited to those resins which contain an oxygen-tin linkage. Antifouling paints based on organic compounds or organometallic monomers are still in the experimental stage; their availability would depend on the success of subsequent coating developments.

The newly developed organotin-polymer-based coatings are anticipated to have a service life of up to 5 yr. This time may be extended by mechanical cleaning. It may be possible to repair and touch up antifouling coatings utilizing coatings similar to epoxy paints developed for underwater application.[109] Accordingly, because of the anticipated service life requirement, developmental antifouling coatings are not now judged suitable for providing long-term antifouling protection for the cold water FRP pipe.

Inherently Antifouling FRP. Inherently antifouling reinforced plastic may be suitable for providing long-term (10- to 15-yr) protection for the OTEC cold water pipe and warm water intake screens. This concept, being developed by the Navy, is based on the synthesis of polyesters and epoxies to which the antifouling tributyltin moieties are chemically attached. Organotin is incorporated chemically in the crosslinking agent which is used to cure commercially available unsaturated polyester resins.[109] Organotin epoxies are produced by incorporating the organotin chemically into the epoxy backbone or curing agent.[110] The epoxies have been the main approach.

Glass-reinforced laminates have been fabricated by using organotin polyesters and organotin epoxies. Technical feasibility has been demonstrated in the manufacture of inherently antifouling glass-reinforced marine structures (e.g., seawater piping systems and sonar domes). Hand lay-up and vacuum bag techniques were employed to fabricate glass-reinforced laminates using glass cloth. Organotin polyester laminate produced by this method was made of an organotin polyester resin cured at room temperature. Glass-reinforced laminates based on organotin epoxies which incorporate the

antifoulant via the organotin curing agent have also been prepared. A second type of glass-reinforced epoxy laminate employing a "shell" laminate concept has been fabricated. The bottom plies of this laminate were laid up as in a conventional epoxy system; the remaining plies were laid up with and organotin epoxy as a "shell" or outer covering over the conventional spoxy system. Both types of laminates were cured at elevated temperatures. Conventional polyester glass-reinforced laminate and a conventional epoxy glass-reinforced laminate were fabricated by using the same technique as for the organotin laminates, for comparison purposes. The flexural strengths and moduli, tensile strengths and moduli, compressive strength, specific gravity, and resin content were determined by ASTM methods. The organotin polyester laminate exhibited only a slight decrease in strength properties compared to the conventional polyester laminate (Table 11).

TABLE 11 - PHYSICAL PROPERTIES OF ORGANOTIN AND CONVENTIONAL LAMINATES

| Property | Epoxy Laminates | | | Polyester Laminates | |
|---|---|---|---|---|---|
| | Organotin | OMP "Shell" | Conventional | Organotin | Conventional |
| Flexural Strength, psi | 56,600 | 65,700 | 72,200 | 55,400 | 63,800 |
| Flexural Modulus, psi | $2.5 \times 10^6$ | $2.8 \times 10^6$ | $3.5 \times 10^6$ | $2.5 \times 10^6$ | $2.7 \times 10^6$ |
| Tensile Strength, psi | 44,100 | 48,200 | 50,500 | 43,400 | 44,800 |
| Tensile Modulus, psi | $2.8 \times 10^6$ | $3.0 \times 10^6$ | $3.3 \times 10^6$ | $3.0 \times 10^6$ | $3.5 \times 10^6$ |
| Compressive Strength, psi | 36,900 | 48,200 | 55,600 | 30,900 | 33,000 |
| Resin Content, % | 38 | 39 | 36 | 43.2 | 40.0 |
| Specific Gravity, g/m | 1.69 | 1.78 | 1.82 | 1.90 | 1.90 |

The organotin epoxy laminate showed a decrease in the strength properties compared to the conventional epoxy laminate. However, the "shell" laminate exhibited only a slight decrease in the strength properties. An oragnotin epoxy laminate showed less than 1-percent water absorption after a year of

long-term water absorption studies. This is comparable to the water absorption of conventional epoxy glass-reinforced laminates. Consequently, organotin epoxy laminates have been fabricated using the "shell" concept. Organotin epoxy glass-reinforced laminates have demonstrated significant antifouling effectiveness at Miami Beach, Florida.

In addition to the epoxy resin formulation described above, organotin epoxy formulations based on cycloaliphatic epoxies, novolac resins, and low molecular weight bisphenol-A epoxy resins have been prepared. Studies leading to optimization of the antifouling effectiveness of these materials are now under way. Of the best antifouling and structural formulation, organotin epoxy preimpregnated (prepreg) glass tapes were manufactured by a commercial company in 1978. Although the use of prepreg tape may not be planned for the construction of the cold water pipe or warm water intake screens, "filament-wound" amd "molded" techniques for the preparation of glass-reinforced organotin plastic have been examined for Navy use in seawater piping systems. Both are considered feasible, and their subsequent application as antifouling GRP could see use in a developmental OTEC plant. The cost of inherently antifouling GRP pipe is difficult to estimate. Development of the concept is now at an early stage. Successful completion of the presently funded programs for development and application of these materials would lead to a field evaluation of prototypes in the early 1980's. The method used to manufacture the GRP pipe and intakes would be important in determining the cost estimate. Cost would either be equal to or greater than fabrication costs of these two components from conventional GRP. It appears that the "shell" fabrication method would be the more cost effective.

W. R. Graner mixed organotin compounds into polyester and epoxy resins and used them to fabricate glass-reinforced laminates.[111] He achieved only short-term antifouling effectiveness. More recently 90-10 Cu-Ni flakes were mixed into conventional polyester resins which then were used as gel coats on glass-reinforced polyester laminates.[112] Short-term antifouling protection was observed. Slime attachment to the gel coat was suggested to be the major factor in reducing the effectiveness of the polyester gel coat; mechanical cleaning was proposed to extend the service life of this coating.

DTNSRDC has been working on the development of gel coats based on organotin epoxy and polyester formulations. Their manufacture is technically feasible.

Antifouling Liners or Sleeves. Protective plastic linings for metal pipe often are used in the chemical industry.[111,113,114] Linings can vary in thickness, application method, and composition.[114] They may consist of resin, such as an epoxy, or of a polyvinyl chloride pressure-sensitive self-adhesive tape; polyethylene sleeving, or glass-reinforced laminated tape.[114] Linings can also incorporate a bactericide if such protection is needed in the specific pipe application.[115] Adaptation of this concept may provide a simple replenishment method of antifouling protection for the OTEC cold water pipe. Liners or sleeves fabricated from a thermoset organotin polymer (polyester or epoxy) of a glass-reinforced thermoset organotin polymer could be positioned at intervals in each pipe section and replaced at given overhaul periods.[116] The applicability of this concept would need further development in order to estimate cost and availability, although the resins basic to this development are still demonstrating antifouling effectiveness after 2 yr of exposure in both temperate and tropical waters.

Summary

Methods for protecting FRP cold water pipe and warm water intake screens have been examined. Commercially available antifouling coatings cannot be used because of their relatively short service life. Developmental coatings which may be available in the early 1980's will be able to provide longer-term antifouling protection (5 yr). This may be extended by periodic mechanical cleaning and touch-up with antifouling coatings which can be applied underwater. Inherently antifouling glass- (fiber-) reinforced plastics might provide long-term (10- to 15-yr) antifouling protection for both the cold water and warm water intake screens. Successful completion of a Navy research program would lead to the limited availability of these materials in the early 1980's and, therefore, availability for use in a developmental OTEC power plant. Cost could be reduced by utilizing a

"shell" concept in the fabrication of components - only surfaces exposed to the seawater would be fabricated with the organotin resin.

## ANTIFOULING CONCRETE

Good mixing practice for structural concrete discourages addition of nonaggregate to the uncured concrete mix. Organic additives, in particular, seriously degrade compressive strength, produce poor bonding of cement to aggregate, and are responsible for overall degradation of desirable structural properties. Therefore, few specific areas of organic antifoulant additions to concrete have been attempted.

### Research to Date

In one study, Muraoka and Vind[12] impregnated porous expanded shale aggregate with various antifouling materials, such as creosote, tributyltin oxide, malachite green, copper naphthenate, and pentachlorophenol. The impregnated shale was substituted for coarse aggregate in concrete mixtures. The resultant concrete than was exposed underwater at representative locations to evaluate the antifouling performance of the cured concrete. Compressive strength and adherence to untreated concrete surfaces also were evaluated. TBTO combined with creosote gave the best performance and remained practically fouling-free for 3 yr. Other systems proved less desirable and fouled after shorter periods. Although the organic antifouling additives lowered the compressive strength of cured concretes, those using solvent-washed and dried impregnated aggregates exhibited compressive strengths of about 3500 psi, which is adequate for marine construction. Also, shear strengths for the adherence of antifouling concrete to conventional concrete was about 1500 psi. Bonding a thick antifouling concrete shell over the main body of conventional structural concrete to various OTEC structures may provide desirable antifouling properties while retaining high structural standards. While bonding fresh mixtures to large areas of fully cured concrete could cause quality control problems, a weaker outer surface may possess desirable renewability properties. Interestingly, the slow deterioration of the outer antifouling shell would constantly expose fresh biologically active sites and extend antifouling protection.

In another experiment, concrete mixtures containing 0.7 to 2.9 percent of a DTNSRDC-developed insoluble acrylic organometallic polymer powder,[116] which exhibited good antifouling performance in static antifouling tests, were prepared and cured. The concrete showed little reduction in compressive strength and exhibited little fouling after 8 months of exposure in the Chesapeake Bay. Further investigation is necessary before this concrete can be considered as a viable antifouling concrete.

### Possible New Methods

Another possible method for providing long-term antifouling protection for OTEC structures is through use of various antifouling polymer-impregnated concrete. The impregnation process[117] involves: (1) absorption of a monomer or partially polymerized system about 1 in. deep in a cured concrete structure, (2) subsequent evaporation of solvent, and (3) polymerization within the concrete. Although polymeric and monomeric antifouling systems have been developed by the Navy and private industry, they have not been used for this specific application.

Polymer concrete consists of aggregate mixed with monomer which is polymerized in place. This concrete has characteristics similar to polymer-impregnated concrete and could use an antifouling monomer system similar to those mentioned above. Polymer concrete has a short curing time and early full strength. However, one disadvantage of this material is its high polymer content (7 to 8 percent by weight); this could increase significantly its costs compared to conventional concrete and could limit the use of polymer concrete to a surface shell coating, similar to the impregnated-shale antifouling concrete described above.

### Cost Estimates

Table 12 presents approximate costs for various raw materials necessary to manufacture the different antifouling concretes.

The costs of concrete vary considerably with geographic location, while the antifouling additive material costs do not. This causes the amount of antifouling material used and the labor intensity of its incorporation in each method to become the critical factors in the determination of the most economically advantageous system. Even though the costs of

TABLE 12 - ANTIFOULING CONCRETE MATERIALS COSTS

| Material | Approximate Average Cost (1977) ($) |
|---|---|
| Marine Concrete, $yd^3$ | 21.00,* 33.00,** 40.00*** |
| Aggregates - Rock & Sand, ton | 2.10,† 8.50 †† |
| Marine Creosote, lb | 0.80††† |
| Tributyltin Oxide, lb | 4.65# |
| Antifouling Polymer Solution, lb | 8.00## |
| Antifouling Monomer Solution, lb | 4.50# |

*Standard Marine Concrete, 3000 psi compressive strength, delivered on-site, Maule Industries, Inc., Miami, Florida.
**Standard Marine Concrete, lightweight concrete, delivered on-site, Maule Industries, Inc., Miami, Florida.
***Standard Marine Concrete, 3000 psi compressive strength, plant cost, HV&D, Honolulu, Hawaii.
† Maule Industries, Inc., Miami, Florida, cost from quarry less transportation.
†† HV&D Company, Inc., Honolulu, Hawaii, cost from quarry including transportation.
††† Koppers Company, Inc., Monroeville, Pennsylvania.
#M&T Chemicals, Rahway, New Jersey.
##45% solids solution, M&T Chemicals, Rahway, New Jersey.

concrete and aggregate vary, they are responsible for only a small fraction of the cost of each proposed system. A brief discussion of these factors for each previously mentioned system follows.

Data supplied by Muroaka and Vind[12] on the impregnated porous shale aggregates indicate that a 25-percent solution of TBTO in marine creosote was most effective in the controlling of fouling at all depths. It is assumed that the porous shale will first absorb 25 to 30 percent by weight of the creosote-TBTO mixture and that the resultant antifouling concrete mixture will be applied as a 3-in.-thick shell over the conventional structural concrete form of the power plant. Table 13 gives cost breakdowns for this system according to geographic location.

The costs are similar regardless of geographic location. However, development of application techniques for covering large surfaces with these concrete shells could conceivably further increase these figures.

TABLE 13 - COST COMPARISON BETWEEN STANDARD CONCRETE AND IMPREGNATED POROUS SHALE ANTIFOULING CONCRETE FOR A 3-IN.-THICK COVERING ($/FT$^2$)

| Location | Standard Concrete | | Antifouling Concrete | |
|---|---|---|---|---|
| | Regular | Lightweight | Regular | Lightweight |
| Florida | 0.19 | 0.31 | 5.08 | 5.20 |
| Hawaii | 0.37 | 0.42 | 5.26 | 5.31 |

In a third method, a polymer impregnation of cured structural concrete surfaces results in a layer of polymer which penetrates to 1 in. below the surface of the concrete. In this case the concrete is expected to absorb 5 percent of the weight of the monomer or polymer solution after solvent evaporation. This produces a flat material cost of approximately $3.13/ft$^2$ for the antifouling organometallic monomer solution. These methods appear to be much cheaper than the impregnated-shale method previously mentioned, but many inherent hidden costs are present in these systems. Even though these materials have exhibited good antifouling performance,[12] they have never been used in this manner, and suitable means of achieving good concrete surface layer penetration must be developed. In addition, with the monomer, free radical polymerization of the antifouling monomer must take place uniformly in the concrete. This has been done in the past by hot water immersion or gamma ray irradiation. A large-scale technique to accomplish this polymerization would have to be developed. These considerations may raise the final cost of these systems to prohibitive levels, but the initial low material costs may merit further investigation in the areas of application and in-situ polymerization.

Finally, in the cost of polymer concrete, it is assumed that this material is applied in a 3-in. surface shell over the structural concrete with monomer comprising 8 percent of the weight of the wet mixture. This produces a cost of approximately $4.67/ft$^2$ in Florida and $4.73/ft$^2$ in Hawaii for polymer concrete, with the antifouling monomer component being the determining cost factor.

### Summary

Antifouling concrete offers a possible, though largely unproven, option for antifouling protection of OTEC concrete structures. Impregnated porous shale antifouling concrete has the proven advantage of small-scale application techniques and documented antifouling performance, but high initial material costs. On the other hand, polymer concrete materials have the advantage of lower initial material costs and promising antifouling performance, but have not as yet been proven in specific concrete applications. In addition, all of these techniques for imparting antifouling properties to concrete have never been attempted on such a large scale and may require the development of costly specialized application procedures for OTEC. This is especially true in the case of the polymeric materials. However, savings resulting from a low-maintenance, antifouling concrete structure could conceivably render this technique cost effective in the long run.

## MECHANICAL CLEANING

In-situ mechanical cleaning techniques have been used to remove dense accumulations of fouling from ships when operational ship requirements precluded the use of dry docking and repainting. Due to increasing fuel costs, mechanical hull cleaning has been viewed as a cost-effective means of fouling control. Rapid expansion in the technology of underwater fouling removal has given the maritime community several competitive methods from which to choose. The following paragraphs will relate ship underwater cleaning technology to the conceptualized OTEC designs.

### Impact of Plant Design

The Lockheed Design[7] has certain features which make the system amenable to in-situ mechanical defouling. The system is not weight critical because the fouling accumulation on exterior surfaces is partially compensated by sufficient reserve buoyancy. An examination of the general configuration of warm and cold water inlets and outlets leads to the following analysis. Mechanical cleaning of the cold water inlet (this also applies to TRW concept)[8] is not being considered; it poses no serious fouling problems. However, the ingestion of large volumes of water may entrap swimming marine

life which could cause obstruction and interference problems. The Lockheed design has removable power modules, each of which contains an evaporator and condenser and related warm water and cold water outlets. The need for periodic underwater maintenance of these structures should be diminished because the removable modules can be refurbished in dry dock. The cold water outlet is located below 90 m in depth where fouling accretion is not expected to be of serious consequence. No further consideration need be given to the underwater maintenance of the cold water exhaust. The upper portion of the Lockheed renewable modules contain the evaporator and warm water exhaust which is about 60 m below the surface. More fouling is expected here than at the cold water exhaust, but the high velocity and open discharge (no screens) should keep fouling within reasonable bounds. No underwater maintenance is projected for the ducts of water exhausts of this design because these surfaces also could be cleaned at dry dock. The critical surfaces that do require attention are the exterior and interior surfaces of the warm water inlet screens and the ducts leading to the evaporator intake. Fouling can be removed in a routine fashion using the system described in the subsequent section together with the conceptualized mechanical aids for access to the screens and ducts. The conceptualized defouling techniques[118] are directed toward the Lockheed model because it is in a more advanced state of geometric definition. While the same approach can apply to other models such as the TRW base line configuration, the dimensions of warm water inlet and warm and cold water exhausts of that design and the depth at which they are located, respectively, are not yet clearly defined. If the ducts are not large enough to be cleaned by multi-brush vehicles, remote control cleaning operations will be required; the apparatus would be positioned by the divers at the time of use. Internal rails could be required to guide the movement of the cleaning device. Of necessity, this would be a more complex system; it would require engineering development of an underwater device equipped with a rotary brush or multihydraulic jets. In general, the mechanical defouling procedure in the warm water intake will scatter debris in a quantity proportional to the amount of fouling. This material must be contained to prevent ingress to the heat exchanger when the plant is restarted after cleaning. Methods to contain and remove the resultant debris will be addressed.

The fouling of the exterior structure (Lockheed concept) containing the crew living quarters will require that the area between the intersection of the screen and a height of 15 ft be cleaned. No technical problems are anticipated. The methods for mechanical defouling of designated surfaces of the OTEC plant will be derived from the state-of-the-art waterborne maintenance procedures for ship hulls. The primary method of cleaning will entail the use of multibrush vehicles, directly or remotely controlled by divers and augmented by hand-operated rotary scrubbers for less accessible areas. Although not fully developed as tools for use by free-swimming divers, jet devices appear to be suitable in cleaning interior surfaces of the warm water inlet, especially at sharp angles and corners. Prior to discussion of state-of-the-art tools and their modification for OTEC application it is necessary to delineate the role and limitations of the diver and to explore the possible use of a modified tethered submersible.

Diver Versus Submersible

Advantages of diver cleaning include:

1. Diver-operated cleaning tools are available.
2. Before and after cleaning, the diver can inspect and photograph the condition of the surface at close quarters.
3. Diver mobility permits access into relatively confined areas.
4. The diver can select from a variety of tools to clean specific surfaces.

Disadvantages of diver cleaning include:

1. Diver is limited by physical constraints of the environment:
    a. Divers cannot work in currents over 3 knots.
    b. Low temperatures limit bottom time.
2. Depth and the necessity to decompress limit his work time.

Advantages of the tethered submersible include:

1. Isolates man from the environment.
2. Eliminates decompression.
3. Increases the underwater working period.

Disadvantages of the submersible include:

1. It requires engineering development for underwater cleaning application. Existing submersibles must be integrated with robot-controlled, exterior-mounted cleaning systems.

2. Large size limits accessibility to confined spaces.

3. Submersible becomes complex when equipped to inspect, document, and clean.

Existing cleaning procedures for underwater hulls are generally not applied deeper than 8 m. Greater depths could be achieved if diver capability is upgraded. Existing underwater cleaning procedures provide divers with surface supplied air. Air diving without decompression[119] limits the cleaning of the OTEC plant to a depth of 15 m because bottom times at greater depths are too short to perform labor-intensive work. Practical bottom times of 1 1/2 hr below 15 m require decompression;[119] therefore, the use of a diving bell to transfer the divers to the surface and a decompression chamber on the deck is necessary. In addition, a minor modification of the cleaning equipment to pressure-proof critical fittings is necessary below 15 m. Extended bottom times at depth below 40 m[120] for 1 1/2 hr or more are feasible, but are further complicated because mixed-gas diving systems are required. Mixed-gas or saturation diving requires greater diver skill and considerable surface support. If OTEC field experience dictates fouling removal at depths below 40 m, the engineering development of a tethered submersible cleaning vehicle may be a simpler and more direct approach. The conceptualized vehicle would have mechanical arms to operate brushes or jets to defoul and a TV camera and video tape equipment to inspect and document the surface conditions before and after cleaning.

### State-of-the-Art Cleaning Equipment

Diver-Operated Rotary Brushes. Many underwater cleaning operations are performed using circular brushes (25 to 36 cm in diameter) fitted to a single diver-held mechanical rotary scrubber (Figure 8). Various types of brushes with different bristle arrangement, bristle length, and materials are available. The bristles may be made of steel, plastic, or plastic-

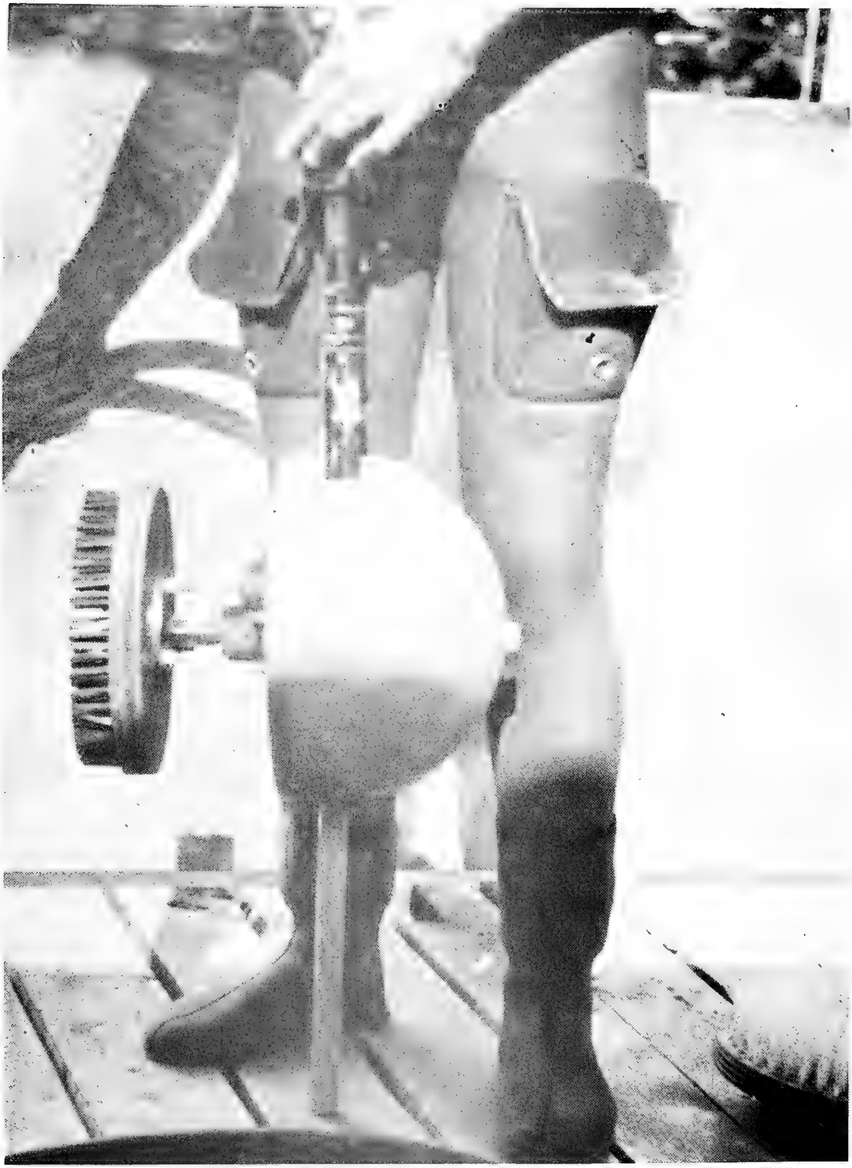

Figure 8 - Diver-Held Mechanical Scrubber

coated steel. Through a proper selection of brushes, a skilled diver can remove fouling from exposed paint, metal, concrete, and plastic surfaces without damage to the surface. Cleaning rates of 80 to 200 $m^2/hr$ have been attained by a diver using a single hand-held rotary brush.[121,122] To operate brushes at depths required for the OTEC plant, the hydraulic hoses for powering the rotary scrubber may have to be lengthened, a modification that may pose interference problems for divers. Efforts might be made to provide the OTEC platform with a hydraulic manifold with quick connection at various depths. In this manner, convenient hose lengths can be used over a wide range of cleaning depths.

Diver-Controlled Multibrush Vehicles. There are two diver-controlled multibrush vehicles that clean underwater surfaces and remove fouling at rates 10 to 20 times faster than single hand-operated rotary brushes.[121,122] These multibrush vehicles are presently the most widely used devices to remove hull fouling.

Submerged Cleaning and Maintenance Platform. SCAMP[TM] is a 1.8-m-diameter, three-brush vehicle.[123-127] It is held against a vertical surface by an independent suction impeller positioned in the center, allowing the angled bristles to skim the hull surface by a shearing action. It is propelled by two motorized rubber wheels, and a third movable wheel provides steering control. The vehicle cleans approximately a 1.7-m swath during each pass. It usually is steered by divers when in use on contoured surfaces, although it can be operated from a workbot by remote control for vertical flat surfaces. The device, Figure 9, and single hand-held diver-operated rotary brushes for the less accessible areas jointly provide the most effective means of fouling removal. A 440-V line from a diesel generator furnishes electric power to motors positioned on the vehicle. The motors operate hydraulic pumps to rotate the brushes, rubber wheels, and suction impeller. There has been some concern in regard to the safety of the 440-V cable extending into the water. According to Exxon, SCAMP will automatically

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[TM]Exxon Corporation.

shut off if there is a break in the line. While SCAMP cannot clean small recesses and ducts, it can clean the interior of ducts larger than 9 m in diameter. The machine can be modified with a longer cable and pressurized seals to operate at greater depths. SCAMP has been used successfully to clean a number of U.S. Navy ships.[123-125]

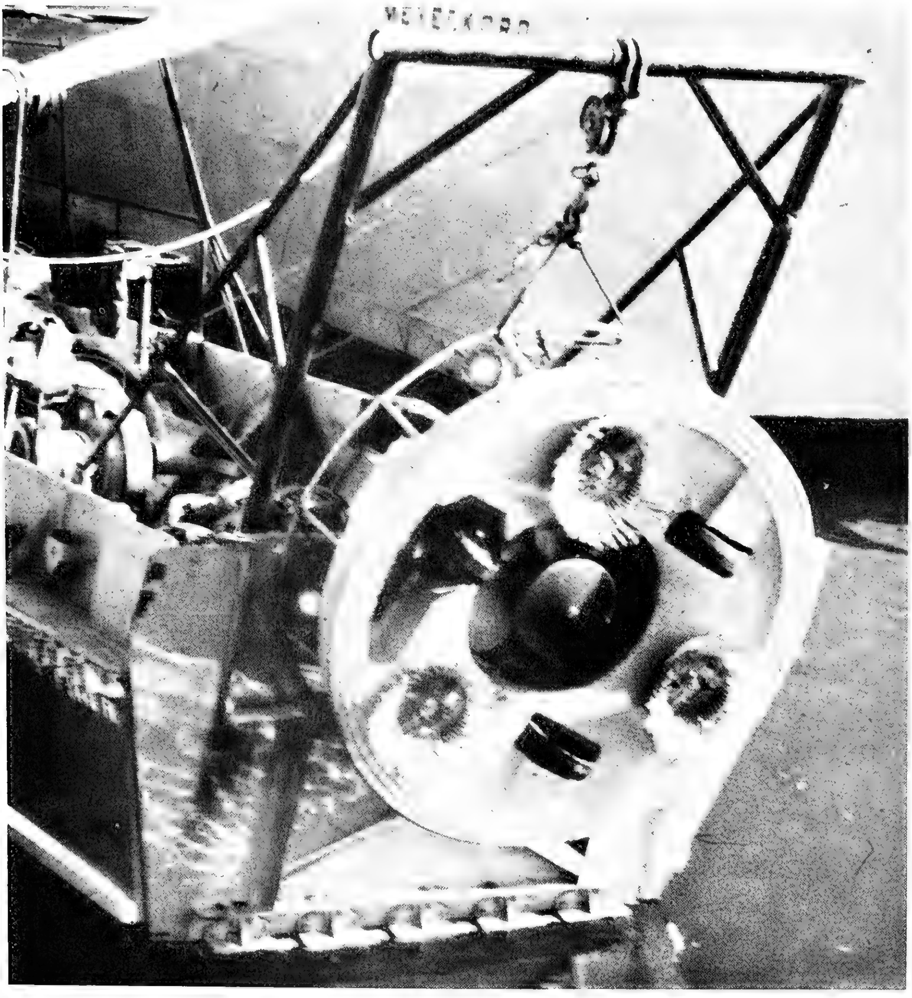

Figure 9 - SCAMP Cleaning Unit

Brush-Kart. The Brush-Kart™ is a diver platform which cleans a 1.2-m swath per pass.[122,123] The unit, Figure 10, is held in contact with the hull by rotary suction of the brushes. The vehicle is steered by divers and cannot operate by remote control. A diesel engine in a workboat operates hydraulic pumps which provide power through two coaxial hydraulic hoses to rotate brushes and drive the rubber wheels on the vehicle. It has been used to clean a few U.S. Navy ships[124] and has been reported to be an effective cleaning-tool system. It probably could be modified to operate at greater depths by pressurizing critical fittings. A convenient hose length operating over a wide range of cleaning depths would be possible if the OTEC platform were equipped with underwater connections providing hydraulic power.

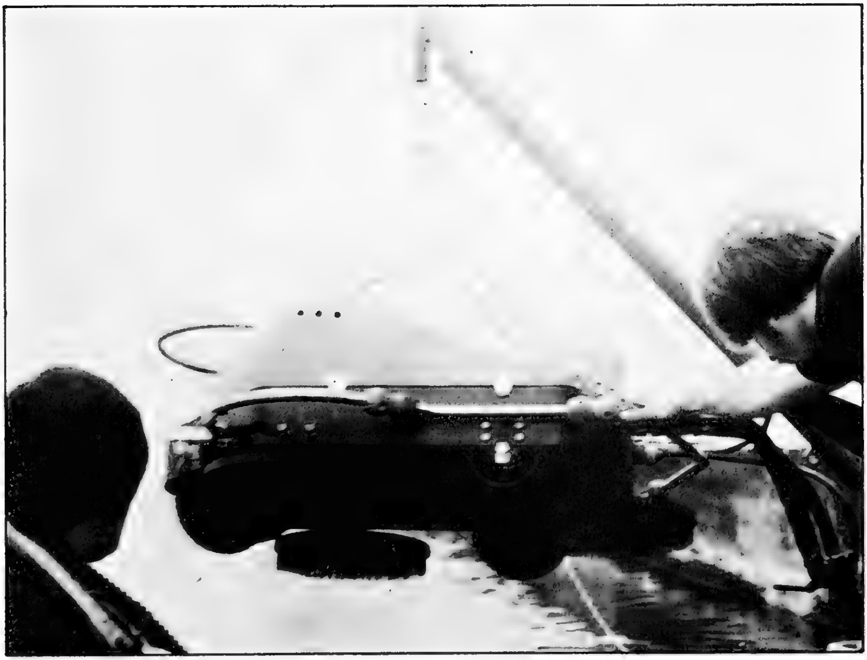

Figure 10 - Brush-Kart Cleaning Unit

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™U.S. Phosmarine, Inc.

Surface Brush Cleaning. Brush-Boat[R] is equipped with a 6-m-long (vertical) cylindrical brush and can be maneuvered about the hull of a ship (Figure 11).[124,126] This vehicle cleans only to a depth of 4 m and, as presently designed, is not considered a candidate for OTEC application. It is mentioned because it suggests possible use in combination with a submersible for cleaning large exterior surfaces.

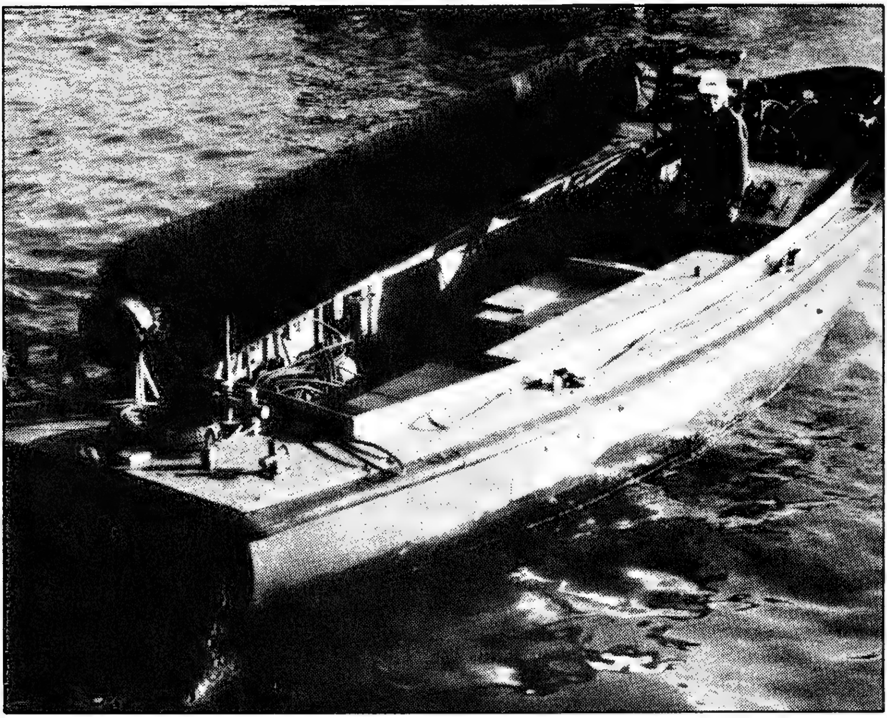

Figure 11 - Brush-Boat Cleaning System

[R] Registered trademark of U.S. Phosmarine, Inc.

Diver-Controlled Jet Cleaning. Hydraulic jet cleaning[123,125,128] has been used to remove debris, loose paint, rust, and scale from ship hulls in dry dock and to clean heat exchangers, reaction vessels, and similar equipment. The simplest jet delivers a stream of water at pressures up to 680 atmospheres (10,000 psi) at 90 l/min. Jet pressure and volume can be controlled to remove fouling and loosely adherent paint without damaging sound coatings. Abrasives can be introduced to increase cleaning effectiveness and rate. Seawater can be used if freshwater is scarce. While effective operation of hydraulic jets by free-swimming divers has not been demonstrated,[125] divers standing on a firm surface underwater have cleaned concrete structures and pilings. If the jet could be modified with compensating thrusters as in Figure 12, operation by free-swimming divers appears feasible.

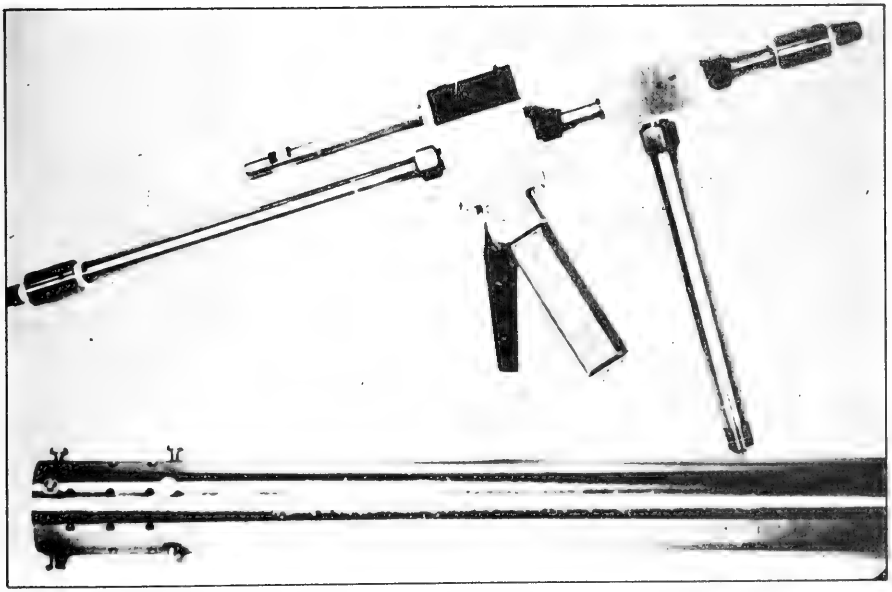

Figure 12 - Hydraulic Jet Cleaning Tool

An effective underwater hydraulic jet unit would be useful mainly for selective cleaning. It would be a desirable addition to the diver's arsenal of equipment for the purpose of cleaning small recesses, ducts, and similar contoured surfaces. Small recesses and ducts cannot presently be cleaned by brushes. Although the single lance jet[129] cannot match the cleaning rate of the rotary brush, a new automatic remote controlled multijet device which is clamped magnetically to the ship's side has been reported.[129,130] This device is purported to be able to clean a ship hull in port or under way. The effectiveness of cleaning is not known. However, it is discussed here because it may be necessary to develop an automatic, remote controlled, multijet device or system to clean the interior ducts of the warm water and cold water exhausts and possibly the warm water inlet.

Cavitation jets[123,125,128,129] are in the preliminary stage of development. Although they have the advantage of operating at much lower pressures than conventional jets, research is necessary to control the powerful impacts which can cut metals. While developments in jetting should be of great interest to OTEC, it is currently not a commercially available underwater cleaning tool.

Required Diver Equipment. The diver requires the following equipment:

1. Surface supplied air using Kirby Morgan KMB-9 masks with communications capability or Jack Brown mask[119] (limited to a depth of 40 m).
2. Diving bell.
3. Decompression chamber.
4. Equipment for mixed-gas systems (for operations below 40 m).[120]
5. Photographic equipment for inspection:
    a. Waterproof 35-mm camera with special close-up lens.
    b. Underwater movie camera, 16 mm.
    c. Underwater strobe flash and movie light.
6. Visual and audio communication equipment - underwater damage and assessment television system (UDATS).

## Feasibility of Mechanical Cleaning

Housing. A system using a combination of multibrush vehicles and hand-held single rotary brushes could remove fouling on all exterior surfaces on either OTEC plant concept. This includes the central platform of the Lockheed concept if it proves to be weight critical in actual service and the exterior of the four power modules, if the surface becomes heavily fouled between dry-docking schedules. To permit driver access to the warm water inlet, the vertical screen of the TRW concept should be attached to the main platform in sections. Each section should be hinged at the upper end and equipped with butterfly lug connections at the lower end. A stop should be provided at the hinges so that the inner surface remains firm when it is being cleaned. The Lockheed warm water inlet screen also could be attached in sections with hinges at the inner circumference and with butterfly lug connections at the outer circumference. However, because of its horizontal design, the entire screen could be raised in one piece. In this case, the screen would float freely and could be positioned by its own negative buoyancy. A stop or projection should be provided to limit the ascent of the screen when it is in the floating mode along the center core. The warm water inlet is cleaned in the following manner:

1. The diver cleans the exterior surface of the screen with SCAMP. This is expected to be more efficient than Brush-Kart on screened surfaces.
2. The divers then attach deflated flotation collars around the outer and inner circumference.
3. The collars are inflated with compressed air to provide sufficient buoyancy to raise the screen vertically using the core section as a guide.
4. The divers clean the interior surface of the ducts leading to the evaporator with a multibrush vehicle.

The SCAMP impeller should be equipped with a flexible manifold which transfers water containing debris to a containment area similar to a scheme patented in Japan.[130] The debris may require containment to prevent its ingress into the heat exchanger during restart. It may be necessary to use a hydraulic jet unit to clean the less accessible areas of the duct. The inside of the warm water inlet should have recessed hand and foot rails.

The rails would provide the diver with grips when he is using the single unit jet. When cleaning is complete, the divers leave the water inlet after all their equipment is removed.

The cleaning of the warm water inlet on the TRW module would proceed in the same fashion except that the vertical hinged screen would be lifted by detachable inflatable buoys.

It is not clear whether divers could gain access to the interior of the warm and cold water exhausts of the TRW module because of size limitations. If they could gain access, they would probably be limited to using a single rotary brush which is too slow and tedious a process. It may be necessary to use an automatic remote control device which is positioned by divers described previously to clean these ducts. These and other connecting ducts may be too small to clean with multibrush vehicles or other semiautomatic devices. They will have to be cleaned by hand-held equipment.

Impact on Cleaned Surfaces. Diver brush cleaning can remove fouling without damaging anticorrosive or antifouling paint systems. Light fouling, slimes, greases, and incipient calcareous forms can be removed by polypropylene brushes without damage to paint.[121] Steel brushes are required to remove heavy fouling, including mature barnacles and tunicates. Skilled divers can clean painted surfaces with steel brushes without damaging the paint film.

Frequency of Cleaning. Cleaning frequency is determined by the maximum amount of fouling not detrimental to plant operation. This can be determined by overall weight increase of the structure and its attendant decrease in reserve buoyancy, and by additional factors such as the rate of refouling which usually accelerates after hull cleaning.[131]

Anchoring Cable. The OTEC anchoring cable is deployed far below critical fouling depths. If fouling removal is required after extended exposure, automated methods would have to be devised. It may be feasible to use an automated underwater cable system based on an adaptation of Drisko's[132] surface preparation and recoating device for guy cables.

Summary

Fouling control by mechanical cleaning of the OTEC plant does not appear to be a severe problem. The critical area that needs attention is the warm water inlet. A systematic underwater mechanical cleaning program is feasible if the methods described above are applied.

The OTEC design should incorporate features which permit easy access by divers to confined areas (inlets and outlets), provide a hydraulic station for underwater connections, and erect suitable grips and guides on internal ducting to simplify diver cleaning operation. Hinged and floating intake screen systems would permit easy access to both sides of the screen. The engineering development of a tethered submersible vehicle equipped with inspection and cleaning devices should be considered.

Electrolytic generation of chlorine in critical areas such as intake screens might be examined as a possible visible alternative. However, the environmental aspects of such usage would have to be examined.

## EXECUTIVE SUMMARY

### DETERIORATION AND CORROSION CONTROL

State of the art for deterioration and corrosion control in the marine environment is advanced. The use of reinforced concrete as a structural material for extended seawater immersion is well accepted provided certain basic guidelines are followed. The long-term preservation of steel members through the combined use of anticorrosion coatings and cathodic protection has been demonstrated. Materials such as titanium are inherently corrosion-resistant while others, such as aluminum, require extra precautions and efforts to maintain their integrity. While problems relating to OTEC are largely attributable to the design and maintenance of a very large structure, additional difficulties related to infrequent overhaul of the main structure may also arise.

### FOULING CONTROL

Active antifouling protection may be limited to 600 ft because evidence indicates most fouling accumulation occurs in the photic zone.

Areas below this depth should have preprogrammed reserve buoyancy to compensate for the anticipated weight increases.

Active antifouling systems recommended for the upper 600 ft are:

1. Main housing - mechanical cleaning as needed, plus additional reserve buoyancy to minimize cleaning frequency.

2. Replaceable modules (including warm and cold water outlets).

    a. Assuming refurbishment of antifouling coatings on a 2-yr basis:

        (1) High-quality, tested copper oxide paint (only in the absence of aluminum heat exchangers).

        (2) High-quality, tested copper oxide - organotin paint (only in the absence of aluminum heat exchangers).

        (3) High-quality, tested organotin paint (for any heat exchanger).

    b. Assuming refurbishment of antifouling coatings on a 5-yr basis - organotin sheeting.

3. Warm water intakes and screens - mechanical cleaning.

4. Pumps.

    a. No antifouling control where velocities exceed 20 knots.

    b. Organotin sheeting on other exposed areas. Types of mechanical cleaning systems have not been specified since design and geometry of a finished OTEC plant have not been decided.

## RECOMMENDATIONS

The following recommendations are offered:

1. Research directed toward design and construction of large cathodic protection systems should be initiated.

2. Development of a reasonable cost, implantable corrosion probe and monitoring system should be undertaken.

3. A list of acceptable anticorrosion paint suppliers should be assembled. Testing selected products will require several years and should commence in the near future.

4. Additional data on rates of open ocean fouling should be assembled for proposed OTEC sites.

5. Current research on the development of novel antifouling coatings and gel coats for fiber-reinforced plastics should be monitored.

6. Lists of acceptable antifouling paint suppliers should be assembled according to type (copper, mixed toxicant with copper, organotin, and organic). Extensive testing of candidate paints should commence in the near future.

7. Suitable mechanical cleaning systems should be developed for OTEC once the basic design has been settled.

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